

**TWO-DIMENSIONAL (2D)  
SURFACE SEISMIC REFLECTION SURVEY**

**at the Sterling Mining Company  
Carroll Hollow Mine,  
Jefferson County, Ohio**

**MSHA Contract # J53R1011**

**Submitted by**

**Lawrence M. Gochioco, P.G.  
LM Gochioco & Associates Inc.**

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## **SUMMARY**

A high-resolution 2D surface seismic reflection project was conducted on July 2005 at the Sterling Mining Company property to detect the old abandoned Sterling Mine works, which closed in 1962. Of greater concern was in the northern reserve area in which the coal company was unsure about the accuracy of the old maps. As such, two surface seismic lines and the first VSP hole were strategically placed to address this issue and because some surface area had limited access. The restricted area is heavily wooded with severe elevation changes with rock outcrops. It was a watershed for natural springs in which the owner uses for his house. Thus, it was easier to have a seismic crew operate inside this restricted area in order to fill a critical data gap in which drilling was not an option.

The final processed surface seismic data sets showed disturbances in the coal seam horizon to be associated with the old mine works. In the area of subsurface coverage beneath Line 1C located to the south, there was a good correlation of detected anomalous coal seam reflections with the estimated mine map locations of the old works. In addition, there were past drilling and hole-to-hole tomography data that supported the interpretation.

On the other hand, seismic data from Line 3A showed a smaller disturbed zone beneath the study area, indicating the old mine works at this location was less extensive than originally thought. The interpretation were confirmed and verified by post-survey drilling and hole-to-hole seismic tomography surveys conducted by the coal company.

Based on the project results conducted at this location, the 2D surface seismic reflection method was successfully demonstrated as a viable technique that can be used to detect old mine works as long as surface conditions are conducive to collect good quality seismic data.

Close interaction with the coal company geologists or engineers is critical to the safe and successful execution of any geophysical investigations as their background knowledge, feedback, and logistical support are invaluable.

## **INTRODUCTION**

On April 26, 2005, LM Gochioco & Associates (LMG&A) Inc. was awarded a contract by the Mine Safety and Health Administration (MSHA), U.S. Department of Labor, to conduct field testing and demonstration of three geophysical methods that could be used to detect air- or water-filled old mine workings or voids. The award included conducting three geophysical methods; namely, vertical seismic profiling (VSP), surface seismic reflection (SSR), and in-seam seismic (ISS), at the Sterling Mining Company (SMC) Carroll Hollow Mine. This report covers the results of the SSR.

Prior to data acquisition, a kick-off meeting was held at MSHA's Pittsburgh Research Center on May 11 in which representatives from District 3 (Pat Betoney) and 5 (Terry Sheffield) were also present because mines selected for this study were located in their district. The kick-off meeting provided useful background information on the respective roles of the contractor and the MSHA

supervising team.

The following day (May 12), the team went to the SMC office in Salineville, OH, and met Tim Miller, geologist, who was our contact person in this geophysical investigation study. Miller provided detailed information about their company's concurrent mining activities, geologic conditions, and concerns about the nearby flooded old Sterling Mine works located northeast of their reserve. Thereafter, we explored the surface conditions where the proposed locations of the SSR lines. It was then that two surface seismic lines were proposed for the northern study area and the southern study area would have one, as shown in **Figure 1**.

## **GEOLOGIC CONDITIONS**

The overburden thickness at the Carroll Hollow Mine ranges from 200 to 350 feet. The surface is mostly gentle rolling hills with open fields and wooded areas. The mine is located in Fox Township, Carroll County, OH. The Mahoning coal (7A) seam is the lowest Conemaugh Age seam in the Pennsylvanian Formation in Ohio. The seam occurs in about 10 square mile area pods which can reach a maximum thickness of 45 inches, usually in the center of the pod. The coal is frequently channeled out on the edges and at times through the center. The coal is also slumped by an overlying shale along the channel margins. The immediate overburden is the black shale grading upward by gray sandy shale and sandstone.

In this mine, the average seam thickness is 34", but the mining height is about 42". The abandoned mine had the same mining height and is water-filled with up to 30 feet of head above the seam elevation. Hydrological testing was based on borehole drilling. The mine dips to the southeast where the pressure head reached up to 65 feet. The immediate roof has bone coal with 7 foot of shale, coarsening up to 5 feet of sandy shale which is then topped by 15 feet of sandstone.

**Figure 1** shows the relative locations of the active mine works of Carroll Hollow Mine, located on the southwest corner of the map. The abandoned and flooded old mine works are shown in turquoise blue, located to the northeast corner of the map. Separating these two mines is a solid blue band with an arrowhead on top that snaked across the reserve block on a north-south trend. This blue band corresponded to previous hole-to-hole tomography surveys conducted by the coal company in the 1990s to image seam continuity, thin coal areas, and to detect mine voids. The tomography surveys were conducted by Gecoh Exploration, a geophysical company based in Lexington, KY. The map also showed washout areas in the reserve in which a major paleochannel system had eroded the seam completely. Based on results from surface drilling, underground observations, and hole-to-hole tomography surveys, the paleochannel system had a north-south trend, which could explain why the old mine works ended abruptly near this boundary. **Figure 2** is an expanded view of the northern study area where surface seismic Lines 2B and 3C are located with respect to the first VSP hole, Kantz05-7.

Tim Miller provided hand-drawn geologic cross sections of two drillholes (see **Figure 3**); namely, Kantz05-7 and Kantz05-13 in which the respective depths to the tops of the coal seam were 261 and 227 ft. The two drillholes are located near seismic survey Lines 2B and 3A and

are approximately 330 ft apart. The first vertical seismic profiling (VSP) survey was conducted in Drillhole Kantz05-7. Drillhole Kantz05-13 was drilled near the western edge of Line 2B. The cross sections show the coal seam is overlain by a sequence of sandstone and sandy shale units.

### **ABANDONED OLD STERLING MINE (closed in 1962)**

The coal company did extensive research work in gathering historical information about the abandoned mine. The Mahoning 7A coal was mined from 1890 to 1962 from a portal along State Route 39 (approximately 5 miles away from the area of interest). The J. M. Hirst and Company was the long time operator. The mine ran submains every 500 ft from which individual rooms were mined and the coal was hand-loaded. Individual rooms usually measured 200 ft long and 24 ft wide. On the western edge of their reserve, some rooms in the south were cut short because of poor roof conditions, thin coal, and washouts. These adverse mining conditions indicated the presence of a nearby paleochannel system.

Ever since the mine was closed, water had been accumulating in the empty chambers, and had built a hydrostatic head of up to 65 ft. above the seam elevation in 2005. Miller's interpretation after reviewing the old Sterling Mine maps appeared to be a simple "cut and paste" job and its accuracy was in question. As a result, SMC conducted a series of hole-to-hole (seismic) tomography surveys in the 1990s to better image the thin coal areas and old mine works. The survey results indicated that errors in the accuracy of the old map could increase as we head further north. The large northern-most room is of greater concern as there were distinct gaps or the lack of pillars in the drawing. However, an outline of the room's western tip was shown and the gap appeared to be linear. Was the absence of pillars the result of poor data transfer from one map to another? If the cut-and-paste method was used, did this process accidentally omit some pillars or entries? Was the old map also accidentally rotated during the process?

To help address these important concerns, the placement of two surface seismic lines were critical. Unfortunately, about two-thirds of the survey lines were located inside heavy woods with severe surface elevation changes, steep slopes, rock outcrops, and natural springs which created adverse conditions for drilling. Securing a drilling permit from the State and permission from the landowner would be extremely difficult as the restricted area is a watershed for natural springs in which the owner uses for his house.

### **HIGH-RESOLUTION 2D SURFACE SEISMIC SURVEY**

There are numerous case studies in which the high-resolution 2D surface seismic reflection method had been successfully demonstrated to enhance a US coal company's exploration program to detect geologic anomalies (washouts, faults, thin coal areas, and rolls) in advance of mine development as well as case studies from foreign countries. Unfortunately, these published case studies were not readily available to the US mining industry as it would require a lot of effort in searching for these papers.

High-resolution surface seismic method can augment an exploration drilling program by

providing continuous subsurface profiles between boreholes (Ziolkowshki and Lerwill, 1979; Ruskey, 1981; Fairbairn, et. Al., 1986; Greenhault et. Al., 1986; Lyatsky and Lawton, 1988; Gochioco and Cotten, 1989; Gochioco and Kelly, 1990; Gochioco, 1991a; Henson and Sexton, 1991.) Conventional 2D surface seismic surveys are conducted to evaluate and image seam continuity and to detect potential geologic seam anomalies and mine voids that could create adverse mining conditions later on. Advances made in the 1980s in three-dimensional (3D) seismic acquisition and processing from the petroleum industry were adopted. There are only a few published case studies in which the high-resolution 3D seismic had been successfully applied in the coal fields (Krey, 1978; Bading, 1986; Lambourne et. al., 1990; and Gochioco, 2000).

LMG&A Inc. replaced the initial proposed seismic acquisition contractor, SeisPros, as they were having problems on a 3D seismic project in Texas and could not meet the company's timetable. As a result, the company subcontracted the acquisition work to Geophex Inc., a company based in North Carolina. Data acquisition at the Carroll Hollow Mine began on July 25, and all the data were collected in three working days.

The southern seismic line is called 1C, and the two northern seismic lines are called 2B and 3A. Total lengths for seismic lines 1C, 2B, and 3A were 1656', 1592', and 1448', respectively. The starting point of each seismic line began from the unprimed letters A, B, and C, and ends with the primed letters A', B', and C'. Appendix 1 shows the surface coordinates taken at 16-ft intervals of the three surface seismic lines, based on Ohio North State Plane coordinates.

Gochioco gained valuable experience when he built Consol's multi-faceted coal geophysics program from 1985 to 2000. He also had extensive hardware resources like Vibroseis, Elastic Wave Generator, 8-gauge seisgun, and 12-gauge seisgun as seismic sources, coupled with single and multiple geophone strings applied to various seam thicknesses and depths (Gochioco, 2005). Given the challenges and target objectives at the Sterling Mine site, the following hardware resources were selected. The Geometrics GEODE system was used as the recorder, employing a 96-channel/shot record with a 12-gauge seisgun as the source. On average, three shots were fired in each source hole to stack the data in order to improve the signal-to-noise ratio. Receivers were single 40-hz geophones. The source interval employed were either 16- or 24-ft, depending on field conditions and data quality.

Recording System	Geometrics Geode
Record Length	0.3 second
Sample Rate	0.125 millisecond
Source	12-gauge Seisgun
Receiver	Single 40-Hz geophone
Receiver Interval	8 ft
Source Interval	16-ft and 24-ft
No. of Channels	96 channels/shot
Nominal Fold	24 - 32
Acquisition Date	July 25 – 27, 2006

TABLE 1 – Key Seismic Data Acquisition Parameters.

**Table 1** above summarizes the key parameters used in data acquisition.

## **DATA PROCESSING**

Processing of the high-resolution 2D surface seismic data is no different from processing petroleum surface seismic reflection data sets. Some minor workflow adjustments and additional testing were needed to enhance the signal-to-noise ratio by attenuating unwanted noisy signals. The generalized data processing workflow is shown below.

1. Assign and QC Geometry information
2. Filter testing
3. Resample data to 0.25 ms
4. Edit or kill bad traces or records
5. Bandpass Filter: 40/60-160/250
6. Automatic Gain Control (AGC): Window = 80 ms, Overlap = 20 ms
7. Airwave mute
8. Apply datum correction (Datum: 1200 ft, Correction Velocity: 9,000 ft/s)
9. 1<sup>st</sup> Break/Refraction mute
10. Apply refraction statics
11. Velocity analysis (1)
12. Normal moveout (NMO) correction (1)
13. Bandpass Filter: 40/60-160/250
14. AGC: Window = 80 ms, Overlap = 20 ms
15. **BRUTE STACK**
16. Apply surface-consistent statics (1) – from Step 14
17. Velocity analysis (2)
18. NMO (2)
19. Bandpass Filter: 40/60-160/250
20. AGC: Window = 80 ms, Overlap = 20 ms
21. **STACK**
22. Apply residual statics (2) – from Step 20
23. Velocity Analysis (3)
24. NMO (3)
25. Bandpass Filter: 40/60-160/250
26. AGC: Window = 80 ms, Overlap = 20 ms
27. Predictive Deconvolution: 20-ms Gap, 10% PW, 150-ms OPL
28. Bandpass Filter: 40/60-160/250
29. AGC: Window = 80 ms, Overlap = 20 ms
30. **FINAL STACK**

## **INTERPRETATION**

In order to enhance the interpretation process, computer modeling in the form of having 2D synthetic seismograms, generated from sonic and density logs, would be useful. However in this

project, it is not critical as the principle investigator has extensive experience in acquiring, processing, and interpreting high-resolution surface seismic data applied to coal. Some of these enhanced interpretation tools such as the seismic interactive interpretation workstation were published in the early 1990s (Gochioco, 1991, and Gochioco, 1992).

The seismic method responds to differences in rock properties based on the product of its density and measured P-wave velocity, called the acoustic impedance (AI). The magnitude of partial reflection and transmission at each rock interface or formation is based on the reflection coefficient, as shown below

$$\text{Reflection Coefficient} = (\rho_2 V_2 - \rho_1 V_1) \div (\rho_2 V_2 + \rho_1 V_1).$$

The numbers 1 and 2 are arbitrary subscripts that denotes successive or sequential rock layers. The principle is rather simple:

- Large AI contrasts – Large reflection amplitude
- Moderate AI contrasts – Moderate reflection amplitude
- No AI contrasts – No reflection

Table 1 shows the comparative AI properties of common rocks based on density and sonic logs.

	Density (g/cc)	Velocity (ft/s)	AI properties
Coal	1.3 – 1.5	7000 – 8000	9,100 – 12,000
Shales	2.2 – 2.4	9000 – 12,000	19,800 – 28,800
Sandstones	2.4 – 2.8	11,000 – 16,000	26,400 – 44,800

As a result of coal's very low AI properties with respect to shales and sandstones, thin coal seams could be detected or imaged by the surface seismic reflection method.

In the seismic imaging world, there are two distinct definitions which is commonly misunderstood and need to be clarified. They are **resolution** and **detection**. In the petroleum industry, many geoscientists like to discuss about resolution because they want to know whether the seismic wavelet can resolve the top and base of a rock layer or reservoir? Resolving power is very dependent on the spectrum of the recorded wavefield. Thus, collecting high-quality broadband data is crucial and resolution can be determined using the one-quarter wavelength ( $\frac{1}{4} \lambda$ ) criteria (Widess, 1973). If the dominant seismic wavelength is 240 ft long, then its resolving power will be 60 ft. That means that the sandstone structure or reservoir has to be at least 60 ft thick in order for the seismic wavelet to resolve its top and bottom layers.

On the other hand, **detection** is different from resolution in which the seismic wavelet can detect a composite sequence of thin stratigraphic units, but cannot resolve the top and bottom of a single geologic unit. Since the coal seam thickness is much thinner than the  $\frac{1}{4} \lambda$  criteria (thickness  $< 1/16 \lambda$ ), the interpreted coal seam reflection is actually composed of some parts of the roof and floor rocks, as long as the composite AI properties is negative, yielding a trough on the seismic section. More detailed discussions to resolve or detect very thin beds and coal seams

were explained by Knapp, 1990, and Gochioco, 1992.

When geophysicists use the term “reflection points”, it is a simplistic term. In reality, the receivers or geophones record seismic energy from a “surface area” of geologic units or reflectors. For coincident source and receiver pairs on the surface, the first central **Fresnel Zone** is circular for a horizontal reflector and is frequency dependent. The radius  $R(1)$  of the first Fresnel Zone is defined as  $R(1) = \text{Square root of } [(D + \lambda/4)(D + \lambda/4) - (D \times D)]$ , where  $D$  is the depth of the reflector. Most of the seismic energy is reflected from the first Fresnel Zone. A simple analogy is to visualize how the light beam from an ordinary flashlight shines on a surface. When the surface is orthogonal to the light beam, the surface area is circular. However, when the light beam strikes the surface at an angle, the surface area becomes an ellipsoid. That is why, placement of surface seismic lines is critical and its orientation with respect to the target objective has to be planned carefully. In this project, we have a situation in which a portion of Line 2B straddled near the edge of the old works. Thus, it is likely that recorded reflections (Fresnel Zone) from the coal seam horizon were getting contributions from both the solid and old mine works, resulting in complex waveforms or signatures different from the other seismic data.

**Figure 4** shows a typical shot gather taken from seismic Line 1C after automatic gain control (AGC) and bandpass filter. **Figures 5 and 6** show shot gathers taken from the two northern seismic Lines 2B and 3A respectively after AGC and bandpass filter were also applied. However, **Figures 5 and 6** had a mute applied to attenuate or remove the airwave noise. Airwave noise is the explosive sound generated by the seisgun as it goes off and the noise propagated along the surface in which the geophones would record. The bottom chart beneath **Figures 4, 5, and 6** corresponded to the surface elevations of the 96 active receivers.

The seismic section is commonly displayed in distance and time. The horizontal scale is called the shotpoint (SP) station and is associated with the surface position of the geophones. Each SP position is equivalent to 8 ft as that was the established receiver interval. Thus, the distance between SP-10 and SP-20 is 80 ft. The vertical scale is measured in time (milliseconds). The recorded two-way travel time is the measured time for the seismic energy to propagate from the surface down to the target horizon and bounces back to the surface geophones.

**Figure 7** is the brute stack of seismic Line 1C. As expected, the brute stack section indicated that seismic data will require more processing to attenuate the unwanted signals while at the same time enhance reflections from the coal seam horizon. Moreover, surface conditions on this site is less than ideal because of the hilly terrain and rock outcrops. Acquisition began on the southwest side at point C (SP-1), and finished at point C' (SP-207).

After undergoing several iterative processes of velocity analyses and statics corrections, the final stack section of Line 1C is presented in **Figure 8**. Based on drillhole data, the average depth of the coal seam ranged from 220 to 265 ft beneath the study area. Using the drillhole data and applying an average RMS velocity of 12,000 ft/s for the overburden thickness, the coal seam reflection (a trough) is interpreted to arrive between 38 and 44 milliseconds (ms). Thus, the most robust and coherent seismic reflection in this section is highlighted in yellow (~ 44 ms). This event is interpreted to be the reflection associated with the target coal seam horizon.

A red horizontal line is drawn across **Figure 8** at the 50-ms timeline to serve as a marker. Near the start and end of each seismic line is where the fold (no. of seismic traces being added together to form a composite trace) is least. This situation is usually called the “roll-in” and “roll-out”, and if the signal-to noise ratio of the seismic data is usually below average, such as this case, it difficult to conduct any interpretation with a degree of confidence as the seismic signals are incoherent. Coherent coal seam reflection appears at about SP-23 and goes on continuously up to SP-53, indicating uniform seam thickness of about 3 ft. The distorted signals from SP-54 to SP-79 indicated subsurface geologic changes that could be associated with thin coal, a washout, or even old mine works. Given the quality of this data set, it is difficult to distinguish one from the other anomaly.

The coal seam reflection re-appears again at about SP-80 and goes on continuously to SP-103. However, the seismic reflection is of lower frequency and amplitude suggesting the polarizing effects of water-filled mine works. Over this interval, the coal seam reflection arrival time remained almost constant at about 44 ms. A major disturbance occurred near SP-105, and followed by a short strip of robust reflection between SP-138 and SP-150. Thereafter, the seismic reflection is highly disturbed, coupled with a delay in arrival time. These two parameters (time delay and disturbed signals) are usually associated with the detection of old abandoned mines. Fractured and water-filled roof rocks typically would scatter the seismic energy and at the same time cause delays in arrival-time because water will slow down the average P-wave velocity in rocks.

Thus, the front end of the old abandoned (Sterling Mine) mine is interpreted to be near SP-80, and extends all the way to the end of the seismic survey line. However, since a major paleochannel system is known to exist at the western edge of the old mine works, the effects of thin coal or washout on the seismic wavelet could be the same as with the old mine works. Hole U03-2 was drilled in 2003 at the edge of the projected old mine works and confirmed its location. The seismic line intersected borehole U03-2 at SP-77. There appears to be a difference (or uncertainty) of about 3 shotpoint stations (between SP-77 and SP-80), which translates to 24 ft. **Figure 9** summarizes the interpretation of Line 1C with intervals or zones of subsurface conditions detected by the seismic reflection method.

The two northern seismic lines intersected each other at respective intersection points of Lines 2B at SP-82 and 3A at SP-103. The brute stack of Line 2B is shown in **Figure 10** - not much to look at but better than the brute stack of Line 1C. Acquisition of this survey line started on the east side (B) and headed westward and finished at B’.

**Figure 11** shows the final stack section of Line 2B and the coal seam reflection is highlighted in yellow. The section shows the coal seam reflection to be continuous indicating almost uniform thickness. It appears, however, that roof rock conditions seemed to vary considerably from SP-56 to SP-108, as indicated by varying roof rock reflection signatures – not the usual clean peak-trough-peak signature. The only major problem shown on this section is between SP-156 and SP-189 in which there is an apparent sag in the coal seam reflection. The “sag” or “apparent roll” feature is too dramatic to be associated with any local geology and could mean an artifact or noise that may result from acquisition and/or processing. Since this problem appeared near the end of the seismic section, it could be ignored as a “roll-out” problem and is uninterpretable.

This interpretation could be supported by examining the surface elevations near the end of Line 2B. From SP-156 to SP-199, the surface elevation dropped dramatically from 1278 to 1217, over a horizontal distance of 344 ft. Such large surface variation can have an adverse effect in the recording and processing of high-resolution shallow seismic data. **Figure 12** summarizes the interpretation of Line 2B with intervals or zones of subsurface conditions detected by the seismic reflection method.

**Figure 13** is the brute stack section of Line 3A, and this stack shows more coherent energy or reflections than the first two brute stacks. Acquisition began on the northern end at point A, and finished at A' to the south.

The final stack section of Line 3A is presented in **Figure 14**. Evidently, this section is the best among the three collected. The coal seam reflection is highlighted in yellow. The coal seam reflection is robust and continuous from the start of the survey line up to SP-98, where a major disturbance could be interpreted as a “fault”. This apparent “fault” appears to have a vertical displacement of over 20 ft. Since we know that shallow faults are not known to exist in this region, then the anomalous feature is likely be associated with the front end of detected old mine works. The apparent “sagging” of the coal seam reflection with respect to near-horizontal shallower reflections indicate an apparent velocity anomaly caused by water saturating the micro-fractures in the roof rocks and filling the empty chambers. This anomaly extends up to SP-132. From SP-132 to the end of the survey line, there appears to be a complete scattering of seismic energy in which no coherent seismic reflections were recorded. This suggests that this part of the old mine works had been mined and the roof rocks were highly fractured.

**Figure 15** summarizes the interpretation of Line 3A with intervals of good coal, and interpreted old mine works with competent and highly-fractured roof rocks.

When you examine the original expanded mine map shown in **Figure 2**, the latter two-thirds of Line 2B was supposed to be completely over old mine works. However, the seismic data collected beneath Line 2B showed a robust and continuous coal seam reflection across this interval. In addition, Line 3A showed the disturbed zone to be slightly smaller in magnitude and concentrated on the southern end of the survey line. These results were unexpected and would require some post-survey verification.

Interpretations from the three surface seismic reflection data sets were integrated into a concurrent mine map provided by Miller. **Figures 16** and **17** show the respective locations (red cross-hatched segments) where disturbances in the coal seam reflection were detected and interpreted to be the estimated boundary of the old Sterling Mine works beneath the survey lines.

## **VERIFICATION**

In October 2005, preliminary results of the surface seismic reflection and VSP data sets were presented to Sterling Mining Corporation because their Fall drilling program was about to start and they needed select surface locations to drill in order to verify the seismic results. Subsurface data collected beneath seismic line 1C correlated very well and confirmed with the known

location of old mine workings in the southern property. The survey line also intersected one previously drilled borehole, U03-2, at SP-77 which was supposed to be located at the known edge of the old works. As expected, hole U03-2 encountered old mine works. Moreover, the seismic data was supported by a nearby borehole, U03-3 where the resultant tomograms generated from hole-to-hole tomography surveys conducted in 2003 between borehole U03-3 and two other boreholes, MON03-6 and MON03-2, indicated solid coal (see **Figure 18**). Thus, SMC saw no need to drill new verification holes in this area as their concurrent mining activity is headed northward and have maintained at least a 200' barrier with respect to the nearest old mine works.

In the northern study area where two surface seismic survey lines were conducted, detected anomalies associated with the old mine works were unfortunately located inside the restricted heavy woods. The wooded area is shaped like an asymmetrical bowl and the lowest elevation point is located near the southeast corner of the intersection of lines 2B and 3A. The surface elevation increases dramatically in the southeast direction, resulting in steep slopes with rock outcrops. The landowner is adversely against drilling on this property as natural springs are presently used for his domestic consumption. Moreover, it would be extremely difficult to secure a drilling permit from the State to drill inside a watershed that has natural springs.

To circumvent this major obstacle and to utilize their past successful experience with hole-to-hole tomography surveys since the early 1990s, SMC drilled a series of boreholes around the perimeter of the wooded area in order to directly and indirectly verify the seismic interpretation. Four closely-spaced boreholes (Kantz05-18, Kantz05-21, Kantz05-21A, and Kantz21B) at about 50-ft centers were drilled near the end of Line 3A. In fact, Kantz05-18 was drilled near SP-175 and encountered old mine works, confirming the seismic interpretation. Further south, boreholes Kantz05-21, Kantz05-21A, and Kantz05-21B encountered solid coal as these holes were outside the area of seismic subsurface coverage. Sterling drilled these three closely-spaced boreholes because the first two holes collapsed because of excessive water in the holes prior to conducting the tomography surveys. On February 2006, SMC drilled another hole (Kantz06-1) at SP-82 of Line 3A to determine the cause of detected anomalous roof reflections. The borehole revealed a relatively thin 28" seam with a 24" shale top.

From the start of the project, SMC had been concerned about the magnitude of old mine works beneath the northern study area. It was a surprise to them when they learned that the scale of disturbance beneath Lines 2B and 3A was smaller in size. In addition, the seismic section beneath Line 2B showed nearly a continuous coal seam reflection across the survey line, indicating no detected mine works. However, a question was raised at the meeting about the seismic reflection method's ability to detect old mine works if the survey line intersected it an angle over a short spatial interval. My response was that it would be very difficult to detect and interpret because of the issue associated with the Fresnel Zone. Thus, SMC selected a few choice locations in the northern perimeter outside of the restricted area. Three boreholes (Kantz05-13, Kantz05-11, and Kantz05-12) along Line 2B were drilled, and their respective shotpoint locations are SP-180, SP-60, and SP-41. Kantz05-11 encountered old works. Boreholes Kantz05-12 and Kantz05-13 encountered solid coal; thus, confirming the results of the seismic data along line 2B. These holes were drilled not only to verify the surface seismic data, but also to plan future hole-to-hole tomography surveys.

Knowing the limited information provided by drilling alone, Sterling drilled four additional holes (Kantz05-20, Kantz05-7A, Kantz05-19, and Kantz05-13) outside the perimeter of the old works and surface seismic lines. These additional holes permitted the company to conduct multiple hole-to-hole tomography surveys in order to enhance the geophysical program in detecting and imaging the old mine works beneath the northern study area.

**Figure 19** shows the results of the hole-to-hole tomography surveys superimposed over the old mine works and surface seismic data. The solid green and yellow line bands between drillholes show solid coal. However, alternating blue and green line bands between holes show detected old mine works. Integrating the results from the surface seismic reflection, drilling, and tomograms, a clearer picture emerges in which the estimated boundaries of the old Sterling Mine works beneath the northern study area begins to take shape. As a result of SMC's past successful experiences with other geophysical technologies, the company has a high degree of confidence in utilizing these valuable geophysical information. Thus, SMC proceeded to develop their future mine plans while maintaining a 200' barrier.

Margin of Error or Uncertainty - Based on my past experiences with 2D high-resolution surface seismic data used to detect subsurface geologic anomalies and man-made structures applied to coal exploration, the margin of error for good quality seismic data is usually +/- 2 SP stations. For example, if the depth of the target coal seam is about 800 ft beneath the surface and a 30-ft receiver interval was used, the estimated margin of error is about +/- 60 ft. When the seismic data quality is considered average, as in this case, the estimated margin of error would increase to about +/- 4 SP stations. This criteria is supported by the example from Line 1C in which borehole U03-2 encountered the known front-end of the old mine works near SP-77, but the interpreted boundary on the seismic section was at SP-80, a difference of 3 SP stations or 24 feet (3 x 8-ft receiver interval).

## **CONCLUSIONS**

As was demonstrated in this field project, the 2D high-resolution surface seismic reflection method is one viable method that can be used to detect old mine works as long as surface conditions are conducive to collecting good quality seismic data. The good correlation of direct and indirect verification of the surface seismic data via drilling and hole-to-hole tomography survey data added value to this project, resulting in higher confidence in interpretation. As in the past, Sterling Mining Corporation has been successful in integrating various subsurface data to help them better plan their future mine development.

Close interaction with the coal company geologists or engineers is critical to the safe and successful execution of any geophysical investigations as their background knowledge, feedback, and logistical support are invaluable.

**Lawrence M. Gochioco, PG**

APPENDIX**1. Ohio North State Plane coordinates of Seismic Line 3A.**

4784	339925.9	2415880	1247.61	0+00a	A1
4856	339910.9	2415886	1246.148	LineA8ftInterval	A3
4863	339895.9	2415891	1244.685	LineA8ftInterval	A5
4670	339880.8	2415897	1243.218	0+48a	A7
4867	339865.8	2415902	1241.831	LineA8ftInterval	A9
4869	339850.8	2415908	1240.439	LineA8ftInterval	A11
4676	339835.8	2415914	1239.047	0+96a	A13
4873	339820.8	2415919	1238.17	LineA8ftInterval	A15
4875	339805.8	2415925	1237.294	LineA8ftInterval	A17
4682	339790.8	2415930	1236.418	1+44a	A19
4879	339775.8	2415936	1235.583	LineA8ftInterval	A21
4881	339760.8	2415941	1234.748	LineA8ftInterval	A23
4688	339745.6	2415947	1233.906	1+92a	A25
4885	339730.8	2415952	1233.346	LineA8ftInterval	A27
4887	339715.8	2415958	1232.781	LineA8ftInterval	A29
4694	339700.6	2415963	1232.211	2+40a	A31
4891	339685.8	2415969	1231.005	LineA8ftInterval	A33
4893	339670.8	2415975	1229.788	LineA8ftInterval	A35
4700	339655.6	2415980	1228.561	2+88a	A37
4897	339640.7	2415986	1226.959	LineA8ftInterval	A39
4900	339625.7	2415991	1225.343	LineA8ftInterval	A41
4706	339610.7	2415997	1223.725	3+36a	A43
4904	339595.7	2416002	1222.061	LineA8ftInterval	A45
4906	339580.7	2416008	1220.394	LineA8ftInterval	A47
4712	339565.9	2416013	1218.751	3+84a	A49
4910	339550.7	2416019	1216.972	LineA8ftInterval	A51
4912	339535.7	2416024	1215.218	LineA8ftInterval	A53
4718	339520.8	2416030	1213.478	4+32a	A55
4916	339505.7	2416036	1211.988	LineA8ftInterval	A57
4918	339490.7	2416041	1210.509	LineA8ftInterval	A59
4724	339475.7	2416047	1209.039	4+80a	A61
4922	339460.7	2416052	1209.487	LineA8ftInterval	A63
4924	339445.6	2416058	1209.933	LineA8ftInterval	A65
4730	339430.7	2416063	1210.378	5+28a	A67
4928	339415.6	2416069	1211.908	LineA8ftInterval	A69
4930	339400.6	2416074	1213.435	LineA8ftInterval	A71
4736	339385.7	2416080	1214.953	5+76a	A73
4934	339370.6	2416086	1215.428	LineA8ftInterval	A75
4936	339355.6	2416091	1215.9	LineA8ftInterval	A77
4742	339340.5	2416097	1216.374	6+24a	A79
4940	339325.6	2416102	1218.213	LineA8ftInterval	A81
4942	339310.6	2416108	1220.059	LineA8ftInterval	A83
4748	339295.5	2416113	1221.917	6+72a	A85

4946	339280.6	2416119	1223.116	LineA8ftInterval	A87
4948	339265.6	2416124	1224.323	LineA8ftInterval	A89
4790	339250.6	2416130	1225.53	nail tp 7+20a	A91
4952	339235.4	2416135	1225.212	LineA8ftInterval	A93
4954	339220.2	2416140	1224.894	LineA8ftInterval	A95
4796	339205.1	2416145	1224.579	7+68a	A97
4958	339189.8	2416150	1223.902	LineA8ftInterval	A99
4960	339174.6	2416155	1223.231	LineA8ftInterval	A101
4802	339159.4	2416160	1222.56	8+16a	A103
4964	339144.3	2416165	1222.159	LineA8ftInterval	A105
4966	339129.1	2416170	1221.758	LineA8ftInterval	A107
4807	339113.8	2416175	1221.355	8+64a	A109
4970	339098.7	2416180	1221.641	LineA8ftInterval	A111
4972	339083.5	2416185	1221.928	LineA8ftInterval	A113
4808	339068.3	2416190	1222.215	9+12a	A115
4976	339052.9	2416195	1222.934	LineA8ftInterval	A117
4978	339037.4	2416199	1223.653	LineA8ftInterval	A119
4814	339022.1	2416203	1224.369	9+60a	A121
4982	339006.5	2416207	1225.927	LineA8ftInterval	A123
4984	338991	2416211	1227.477	LineA8ftInterval	A125
4820	338975.5	2416215	1229.03	10+08a	A127
4988	338960.1	2416219	1231.848	LineA8ftInterval	A129
4990	338944.6	2416223	1234.671	LineA8ftInterval	A131
4826	338929.2	2416227	1237.491	10+56a	A133
4994	338913.7	2416232	1241.066	LineA8ftInterval	A135
4996	338898.3	2416236	1244.637	LineA8ftInterval	A137
4832	338882.8	2416240	1248.201	11+04a	A139
5000	338868.2	2416246	1252.173	LineA8ftInterval	A141
5002	338853.7	2416253	1256.137	LineA8ftInterval	A143
4838	338839.2	2416260	1260.071	11+52a	A145
5105	338824.5	2416266	1262.629	LineA8ftInterval	A147
5107	338810	2416273	1265.168	LineA8ftInterval	A149
4844	338795.3	2416280	1267.715	12+00a	A151
5111	338780.7	2416286	1269.593	LineA8ftInterval	A153
5113	338766.1	2416292	1271.476	LineA8ftInterval	A155
4778	338751.4	2416299	1273.361	12+48a	A157
5117	338736.8	2416305	1276.169	LineA8ftInterval	A159
5119	338722.1	2416312	1278.979	LineA8ftInterval	A161
4772	338707.5	2416318	1281.777	12+96a	A163
5123	338692.7	2416324	1284.755	LineA8ftInterval	A165
5125	338678	2416331	1287.719	LineA8ftInterval	A167
4766	338663.5	2416337	1290.666	13+44a	A169
5129	338648.7	2416343	1294.807	LineA8ftInterval	A171
5131	338634	2416350	1298.923	LineA8ftInterval	A173
4760	338619.4	2416356	1303.036	13+92a	A175
5135	338604.7	2416362	1306.903	LineA8ftInterval	A177
5137	338590	2416369	1310.768	LineA8ftInterval	A179
4754	338575.3	2416375	1314.623	14+40a	A181

2. Ohio North State Plane coordinates of Seismic Line 2B.

4623	339244.7	2415494	1245.191	00b	B1
4666	339243.3	2415510	1245.242	LineB8ftInterval	B3
4668	339242	2415525	1244.483	LineB8ftInterval	B5
4613	339240.7	2415541	1246.899	0+48b	B7
4672	339239.4	2415557	1247.39	LineB8ftInterval	B9
4674	339238	2415573	1247.882	LineB8ftInterval	B11
4614	339236.7	2415589	1248.379	0+96b	B13
4678	339235.4	2415605	1248.595	LineB8ftInterval	B15
4680	339234	2415621	1248.814	LineB8ftInterval	B17
4616	339232.7	2415637	1249.033	1+44b	B19
4684	339231.4	2415653	1248.64	LineB8ftInterval	B21
4686	339230.1	2415669	1248.246	LineB8ftInterval	B23
4612	339228.7	2415685	1247.852	1+92b	B25
4690	339227.4	2415701	1247.625	LineB8ftInterval	B27
4692	339226.1	2415717	1247.399	LineB8ftInterval	B29
4615	339224.7	2415733	1247.17	2+40b	B31
4696	339223.4	2415749	1247.218	LineB8ftInterval	B33
4698	339222.1	2415765	1247.266	LineB8ftInterval	B35
4617	339220.8	2415781	1247.313	2+88b	B37
4702	339219.4	2415797	1247.672	LineB8ftInterval	B39
4704	339218.1	2415812	1248.03	LineB8ftInterval	B41
4618	339216.7	2415829	1248.393	3+36b	B43
4708	339215.4	2415844	1248.516	LineB8ftInterval	B45
4710	339214.1	2415860	1248.641	LineB8ftInterval	B47
4619	339212.8	2415876	1248.765	3+84b	B49
4714	339211.5	2415892	1248.422	LineB8ftInterval	B51
4716	339210.2	2415908	1248.078	LineB8ftInterval	B53
4624	339208.9	2415924	1247.734	nail tp 4+32b	B55
4720	339205.1	2415940	1246.823	LineB8ftInterval	B57
4722	339201.4	2415955	1245.91	LineB8ftInterval	B59
4620	339197.6	2415971	1244.989	4+80b	B61
4726	339193.9	2415986	1244.79	LineB8ftInterval	B63
4728	339190.2	2416002	1244.59	LineB8ftInterval	B65
4621	339186.5	2416017	1244.39	5+28b	B67
4732	339182.7	2416033	1243.903	LineB8ftInterval	B69
4734	339179	2416049	1243.417	LineB8ftInterval	B71
4622	339175.3	2416064	1242.932	5+76b	B73
4738	339171.5	2416080	1241.316	LineB8ftInterval	B75
4740	339167.8	2416095	1239.702	LineB8ftInterval	B77
4635	339164	2416111	1238.084	nail 6+24b	B79
4744	339162	2416127	1233.289	LineB8ftInterval	B81
4746	339159.9	2416142	1228.484	LineB8ftInterval	B83
4645	339157.8	2416158	1223.662	6+72b	B85
4750	339155.7	2416174	1221.248	LineB8ftInterval	B87

4752	339153.6	2416190	1218.827	LineB8ftInterval	B89
4641	339151.6	2416206	1216.47	+20b	B91
4756	339148.4	2416222	1217.814	LineB8ftInterval	B93
4758	339145.1	2416237	1219.231	LineB8ftInterval	B95
4646	339141.9	2416253	1220.653	7+68b	B97
4762	339137.8	2416268	1227.722	LineB8ftInterval	B99
4764	339133.6	2416284	1234.813	LineB8ftInterval	B101
4647	339129.5	2416299	1241.805	8+06b	B103
4768	339124.4	2416315	1244.636	LineB8ftInterval	B105
4770	339119.4	2416330	1247.429	LineB8ftInterval	B107
4649	339114.4	2416345	1250.207	8+64b	B109
4774	339108.5	2416360	1252.641	LineB8ftInterval	B111
4776	339102.7	2416375	1255.062	LineB8ftInterval	B113
4650	339096.9	2416389	1257.466	9+12b	B115
4780	339091	2416404	1259.956	LineB8ftInterval	B117
4782	339085.1	2416419	1262.428	LineB8ftInterval	B119
4651	339079.4	2416434	1264.867	9+60b	B121
4786	339073.5	2416449	1267.352	LineB8ftInterval	B123
4788	339067.6	2416464	1269.803	LineB8ftInterval	B125
4652	339061.8	2416479	1272.23	10+08b	B127
4792	339055.9	2416494	1274.42	LineB8ftInterval	B129
4794	339050.1	2416509	1276.588	LineB8ftInterval	B131
4653	339044.3	2416523	1278.736	10+56b	B133
4798	339038.4	2416539	1280.889	LineB8ftInterval	B135
4800	339032.6	2416553	1283.023	LineB8ftInterval	B137
4654	339026.7	2416568	1285.15	11+04b	B139
4804	339020.9	2416583	1286.37	LineB8ftInterval	B141
4806	339015	2416598	1287.586	LineB8ftInterval	B143
4655	339012.2	2416613	1287.99	11+52	B145
4810	339012.1	2416630	1286.659	LineB8ftInterval	B147
4812	339012	2416646	1285.336	LineB8ftInterval	B149
4656	339011.9	2416661	1284.033	12+00b	B151
4816	339011.9	2416678	1281.844	LineB8ftInterval	B153
4818	339011.8	2416694	1279.689	LineB8ftInterval	B155
4657	339011.7	2416709	1277.557	12+48b	B157
4822	339011.6	2416726	1275.703	LineB8ftInterval	B159
4824	339011.6	2416742	1273.869	LineB8ftInterval	B161
4658	339011.5	2416757	1272.056	12+96b	B163
4828	339011.4	2416774	1269.123	LineB8ftInterval	B165
4830	339011.3	2416790	1266.224	LineB8ftInterval	B167
4659	339011.3	2416805	1263.347	13+44b	B169
4834	339011.2	2416822	1260.453	LineB8ftInterval	B171
4836	339011.1	2416838	1257.582	LineB8ftInterval	B173
4660	339011	2416853	1254.735	13+92b	B175
4840	339011	2416870	1252.323	LineB8ftInterval	B177
4842	339010.9	2416886	1249.932	LineB8ftInterval	B179
4661	339010.8	2416901	1247.569	14+40b	B181
4846	339011.9	2416918	1246.247	LineB8ftInterval	B183

4848	339013	2416934	1244.941	LineB8ftInterval	B185
4663	339014.1	2416949	1243.665	14+88b	B187
4852	339017	2416965	1240.428	LineB8ftInterval	B189
4854	339019.9	2416981	1237.267	LineB8ftInterval	B191
4662	339022.7	2416996	1234.169	nail tp 15+36b	B193
4858	339025.7	2417012	1228.647	LineB8ftInterval	B195
4860	339028.5	2417028	1223.234	LineB8ftInterval	B197
4664	339031.4	2417044	1217.942	15+84b	B199

### 3. Ohio North State Plane coordinates of Seismic Line 1C.

4871	335527.1	2415908	1295.852	SS01 0+00c	C1
5149	335539.5	2415918	1291.679	LineC8ftInterval	C3
5336	335551.9	2415928	1287.505	LineC8ftInterval	C5
4877	335564.2	2415938	1283.342	0+48c	C7
5339	335576.7	2415948	1278.716	LineC8ftInterval	C9
5403	335589	2415959	1274.102	LineC8ftInterval	C11
4883	335601.4	2415969	1269.499	0+96c	C13
5499	335613.8	2415979	1266.268	LineC8ftInterval	C15
5501	335626.2	2415989	1263.045	LineC8ftInterval	C17
4889	335638.7	2415999	1259.795	1+44c	C19
5504	335651	2416009	1255.888	LineC8ftInterval	C21
5506	335663.4	2416019	1251.949	LineC8ftInterval	C23
4895	335675.7	2416029	1248.029	1+92c	C25
5509	335688.1	2416040	1245.334	LineC8ftInterval	C27
5511	335700.5	2416050	1242.653	LineC8ftInterval	C29
4902	335712.6	2416059	1240.052	2+40c	C31
5514	335725.3	2416070	1237.651	LineC8ftInterval	C33
5516	335737.7	2416080	1235.32	LineC8ftInterval	C35
4908	335750	2416090	1233.013	2+88c	C37
5519	335762.5	2416100	1231.052	LineC8ftInterval	C39
5521	335774.9	2416110	1229.112	LineC8ftInterval	C41
4914	335787.3	2416121	1227.167	3+36c	C43
5524	335799.6	2416131	1225.416	LineC8ftInterval	C45
5527	335812	2416141	1223.662	LineC8ftInterval	C47
4920	335824.4	2416151	1221.914	3+84c	C49
5533	335836.8	2416161	1219.743	LineC8ftInterval	C51
5535	335849.2	2416171	1217.581	LineC8ftInterval	C53
4926	335861.5	2416181	1215.434	4+32c	C55
5538	335874	2416191	1212.423	LineC8ftInterval	C57
5540	335886.4	2416202	1209.434	LineC8ftInterval	C59
4932	335898.6	2416212	1206.481	4+80c	C61
5543	335911.1	2416222	1203.695	LineC8ftInterval	C63
5545	335923.5	2416232	1200.944	LineC8ftInterval	C65
4938	335935.9	2416242	1198.193	5+28c	C67
5548	335948.3	2416252	1197.782	LineC8ftInterval	C69
5550	335960.7	2416262	1197.37	LineC8ftInterval	C71

4944	335973.1	2416272	1196.96	5+76c	C73
5553	335985.5	2416283	1195.616	LineC8ftInterval	C75
5596	335994.4	2416295	1192.161	LineC8ftInterval	C77
4956	336001.4	2416310	1187.513	6+24c	C79
5599	336008.4	2416324	1186.297	LineC8ftInterval	C81
5601	336015.4	2416339	1185.087	LineC8ftInterval	C83
5603	336022.3	2416353	1183.877	LineC8ftInterval	C85
5604	336029.3	2416367	1184.966	LineC8ftInterval	C87
5606	336036.3	2416382	1188.331	LineC8ftInterval	C89
4968	336043.3	2416396	1191.71	7+20c	C91
5609	336050.2	2416411	1194.114	LineC8ftInterval	C93
5611	336057.2	2416425	1196.528	LineC8ftInterval	C95
4974	336064.1	2416439	1198.933	7+68c	C97
5642	336071.1	2416454	1201.051	LineC8ftInterval	C99
5680	336078.1	2416468	1203.161	LineC8ftInterval	C101
4980	336085.1	2416483	1205.261	8+16c	C103
5838	336092.1	2416497	1207.964	LineC8ftInterval	C105
5840	336099	2416511	1210.654	LineC8ftInterval	C107
4986	336106	2416526	1213.333	8+64c	C109
5843	336113	2416540	1213.679	LineC8ftInterval	C111
5888	336120	2416555	1214.023	LineC8ftInterval	C113
4992	336126.9	2416569	1214.367	9+12c	C115
5891	336133.9	2416583	1215.153	LineC8ftInterval	C117
5893	336140.9	2416598	1215.939	LineC8ftInterval	C119
5147	336148.6	2416612	1216.277	9+60c	C121
5896	336159.4	2416624	1217.403	LineC8ftInterval	C123
5898	336170.1	2416635	1218.534	LineC8ftInterval	C125
5146	336181	2416647	1219.679	10+08c	C127
5901	336191.7	2416659	1220.474	LineC8ftInterval	C129
5904	336202.4	2416671	1221.279	LineC8ftInterval	C131
5145	336213.2	2416683	1222.087	10+56c	C133
5907	336224	2416695	1222.198	LineC8ftInterval	C135
5909	336234.7	2416706	1222.308	LineC8ftInterval	C137
5144	336245.6	2416718	1222.42	11+04c	C139
5912	336256.3	2416730	1222.969	LineC8ftInterval	C141
5915	336267	2416742	1223.523	LineC8ftInterval	C143
5143	336277.8	2416754	1224.08	11+52c	C145
5918	336288.6	2416766	1224.842	LineC8ftInterval	C147
5920	336299.3	2416777	1225.606	LineC8ftInterval	C149
5142	336310.2	2416789	1226.375	12+00c	C151
5923	336320.9	2416801	1227.405	LineC8ftInterval	C153
5925	336331.6	2416813	1228.442	LineC8ftInterval	C155
4998	336343.3	2416826	1229.459	SS4	C157
5928	336354.8	2416835	1229.54	LineC8ftInterval	C159
5930	336367.4	2416845	1229.627	LineC8ftInterval	C161
5140	336380.2	2416855	1229.716	12+96c	C163
5933	336392.6	2416864	1230.048	LineC8ftInterval	C165
5935	336405.2	2416874	1230.385	LineC8ftInterval	C167

5139	336417.7	2416884	1230.722	13+44c	C169
5938	336430.3	2416894	1230.193	LineC8ftInterval	C171
5940	336442.9	2416904	1229.663	LineC8ftInterval	C173
5133	336455.5	2416914	1229.131	13+92c	C175
5945	336468.1	2416924	1230.804	LineC8ftInterval	C177
5947	336480.6	2416934	1232.487	LineC8ftInterval	C179
5127	336493.2	2416944	1234.173	14+40c	C181
5950	336505.8	2416953	1234.898	LineC8ftInterval	C183
5952	336518.4	2416963	1235.624	LineC8ftInterval	C185
5121	336531.2	2416973	1236.364	14+88c	C187
5955	336543.5	2416983	1236.762	LineC8ftInterval	C189
5957	336556.1	2416993	1237.167	LineC8ftInterval	C191
5115	336568.8	2417003	1237.575	15+36c	C193
5960	336581.3	2417013	1237.777	LineC8ftInterval	C195
5962	336593.8	2417023	1237.981	LineC8ftInterval	C197
5109	336606.5	2417033	1238.186	15+84c	C199
5965	336619	2417042	1238.901	LineC8ftInterval	C201
5967	336631.6	2417052	1239.624	LineC8ftInterval	C203
5969	336644.2	2417062	1240.346	LineC8ftInterval	C205
5971	336656.7	2417072	1241.068	LineC8ftInterval	C207

**REFERENCES**

Bading, R., 1986, How to optimize 3D seismic land surveys – some rules for areal data gathering, in Buchanan, D.J. and Jackson, L. J., Eds. Coal Geophysics: Soc Expl. Geophys Reprint 6, 211-236.

Fairbairn, C. M., Holt, J. M., and Padgett, N. J., 1986, Case histories of the use of surface seismic method in the UK coal mining industry, Buchanan, D.J. and Jackson, L. J., Eds. Coal Geophysics: Soc Expl. Geophys Reprint 6, 188-203.

Gochioco, L. M., 1991, Advances in seismic reflection profiling in US coal exploration: The Leading Edge, 10, No. 12, 24-29.

Gochioco, L. M., 1991, Applications of the seismic interactive interpretation workstation for the coal industry: Mining Engineering, 43, 8, 1057-1061.

Gochioco, L. M., 1992, Modeling studies of interference reflections in thin-layered media bounded by coal seams: Geophysics, 57, 9, 1209-1216.

Gochioco, L. M., 2000, High-resolution 3D seismic survey over a coal mine reserve area in the US – a case study, Geophysics, 65, 3, 712-718.

Gochioco, L. M., 2005, Will geophysical technologies return to US coal fields?: Mining Engineering, 57, 8, 27-33.

Gochioco, L. M., and Cotten, S. A., 1989, Locating faults in underground coal mines using high-resolution seismic reflection technique: Geophysics, 54, 12, 1521-1527.

Gochioco, L. M. and Kelly, J. I., 1990, High-resolution seismic surveys to map paleochannels in an underground coal mine: Can. Jour. Explor. Geophys, 26, 2, 87-93.

Greenhalgh, S., Suprajitno, M., and King, D., 1986, Shallow seismic reflection investigation of coal in the Sydney Basin: Geophysics, 61, 1426-1437.

Henson, H. and Sexton, J. L., 1991, Preliminary study of shallow coal seams using high-resolution seismic reflection method: Geophysics, 56, 1494-1503.

Knapp, R. W., 1990, Vertical resolution of thick beds, thin beds, and thin bed cyclothems: Geophysics, 55, 1184-1191.

Krey, T., 1978, Reconciling the demands of 3D seismics with those of improved resolution: Presented at 48<sup>th</sup> Ann. Mtg. Soc. Explor. Geophys.

Lambourne, A. N., Evans, B. J., and Hatherly, P., 1990, Areal coal seam mapping by 3D seismic reflection surveying – a case history from the Sydney Basin, Australia: 60<sup>th</sup> Ann. Internl. Mtg. Soc. Explor. Geo., Expanded Abstracts, 726-728.

Lyatsky, H., Lawton, D., 1988, Application of the surface seismic reflection method to shallow coal exploration in the plains of Alberta, Canada: Can. Jour. Expl. Geophys, 24, 2, 124-140.

Ruskey, F., 1981, High-resolution seismic methods for hard rock mining: US Bureau Mines Information Circular 8891, 4-28.

Ziolkowski, A., and Lerwill, W. E., 1979, A simple approach to high-resolution seismic profiling for coal: Geophys Prosp., 27, 360-393.

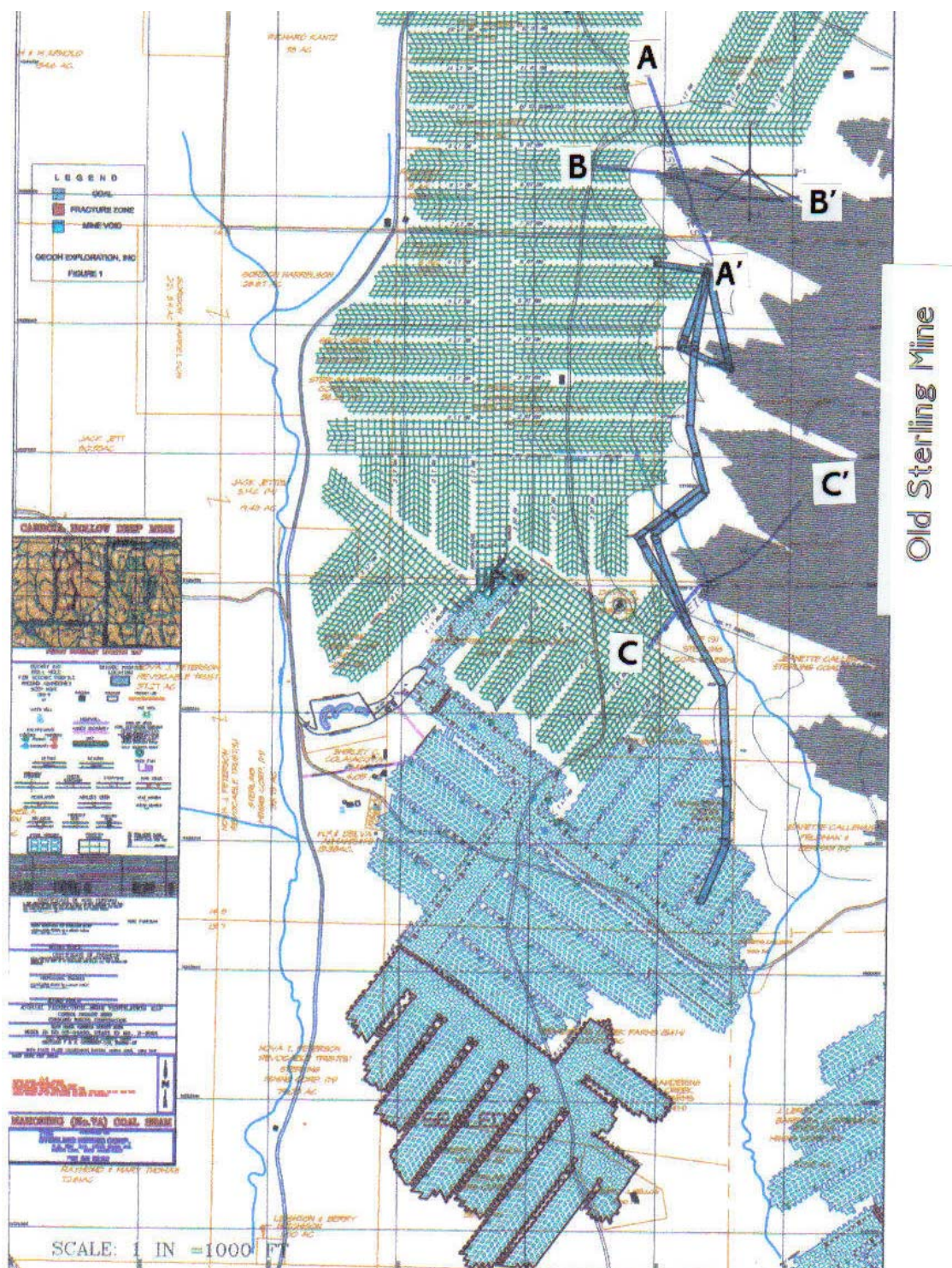


Figure 1. Map of study area showing the relative locations of the three surface seismic lines (A-A', B-B', and C-C') with respect to the old Sterling Mine located to the northeast. Seismic survey lines were chosen based on good surface access and on the latest knowledge of locations of old mine works, as indicated by the dark shaded areas.

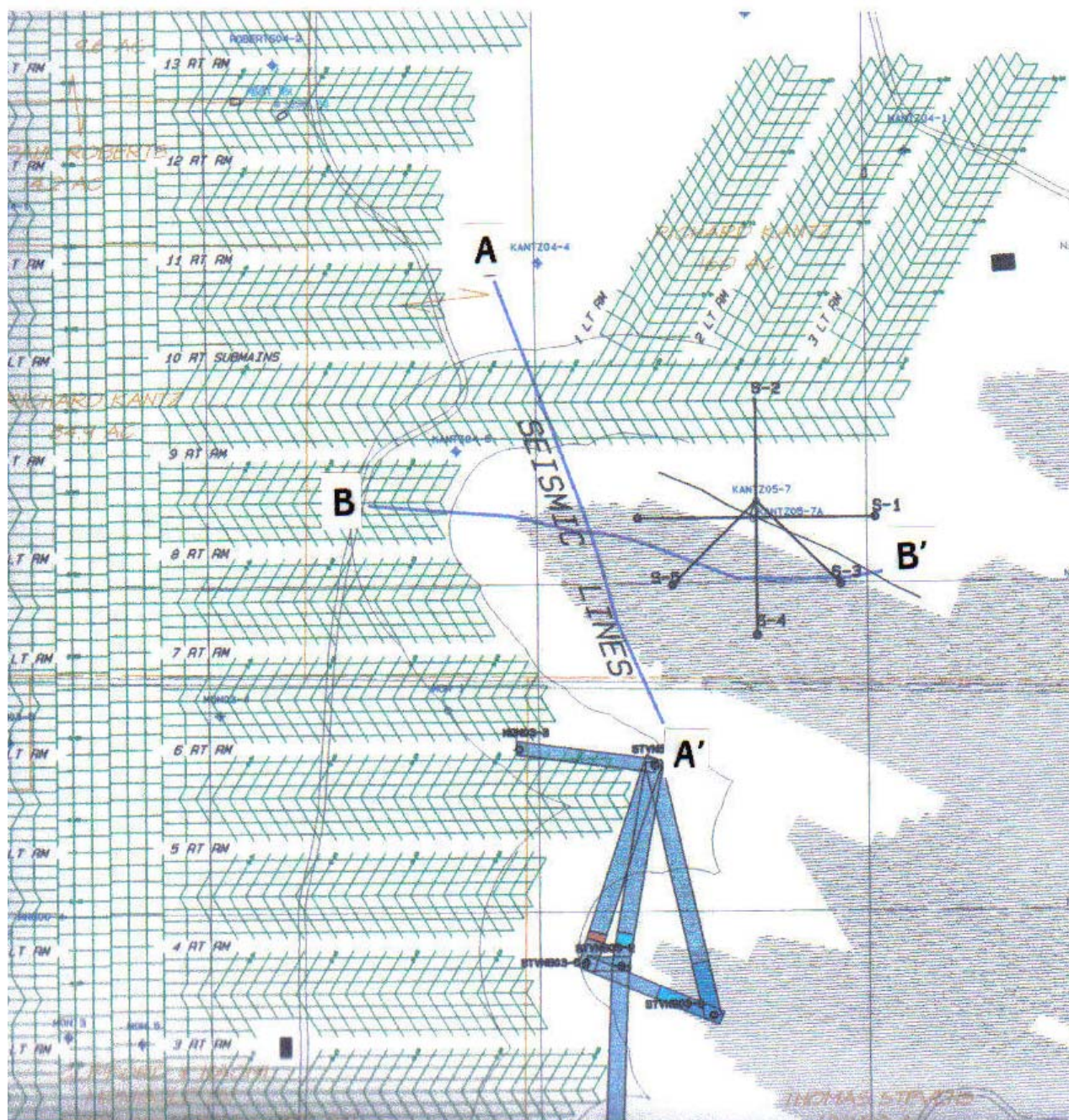


Figure 2. Expanded scale of study area showing the surface seismic Lines 2B and 3A with respect to the VSP hole and the old Sterling Mine works (solid shaded, right). The blue-shaded arrow-head like diagram is associated with hole-to-hole tomography surveys conducted by the coal company. Placement of the seismic survey lines and the VSP hole were based on the concurrent understanding and interpretations of projected mine works.

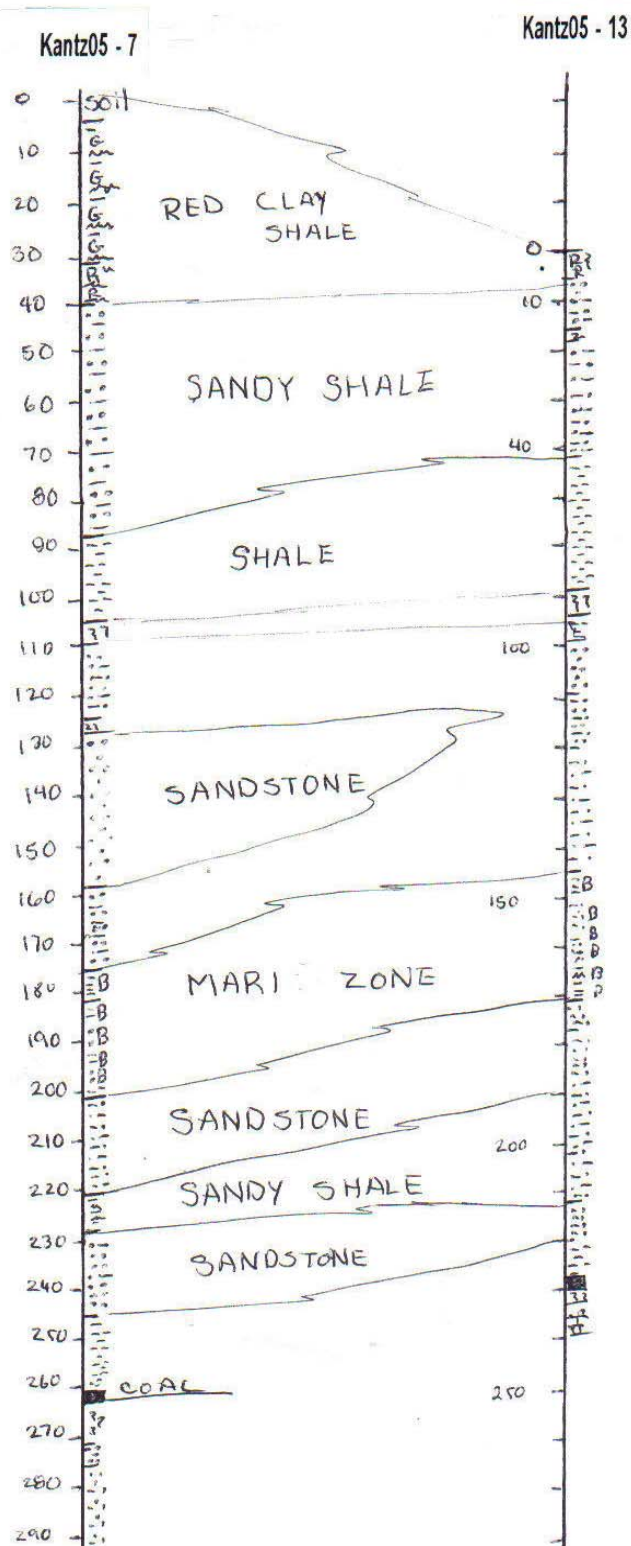


Figure 3. Geologic cross section of two drillholes (Kantz05-7 and Kantz05-13) provided by geologist, Tim Miller. The two holes are about 330 ft apart.

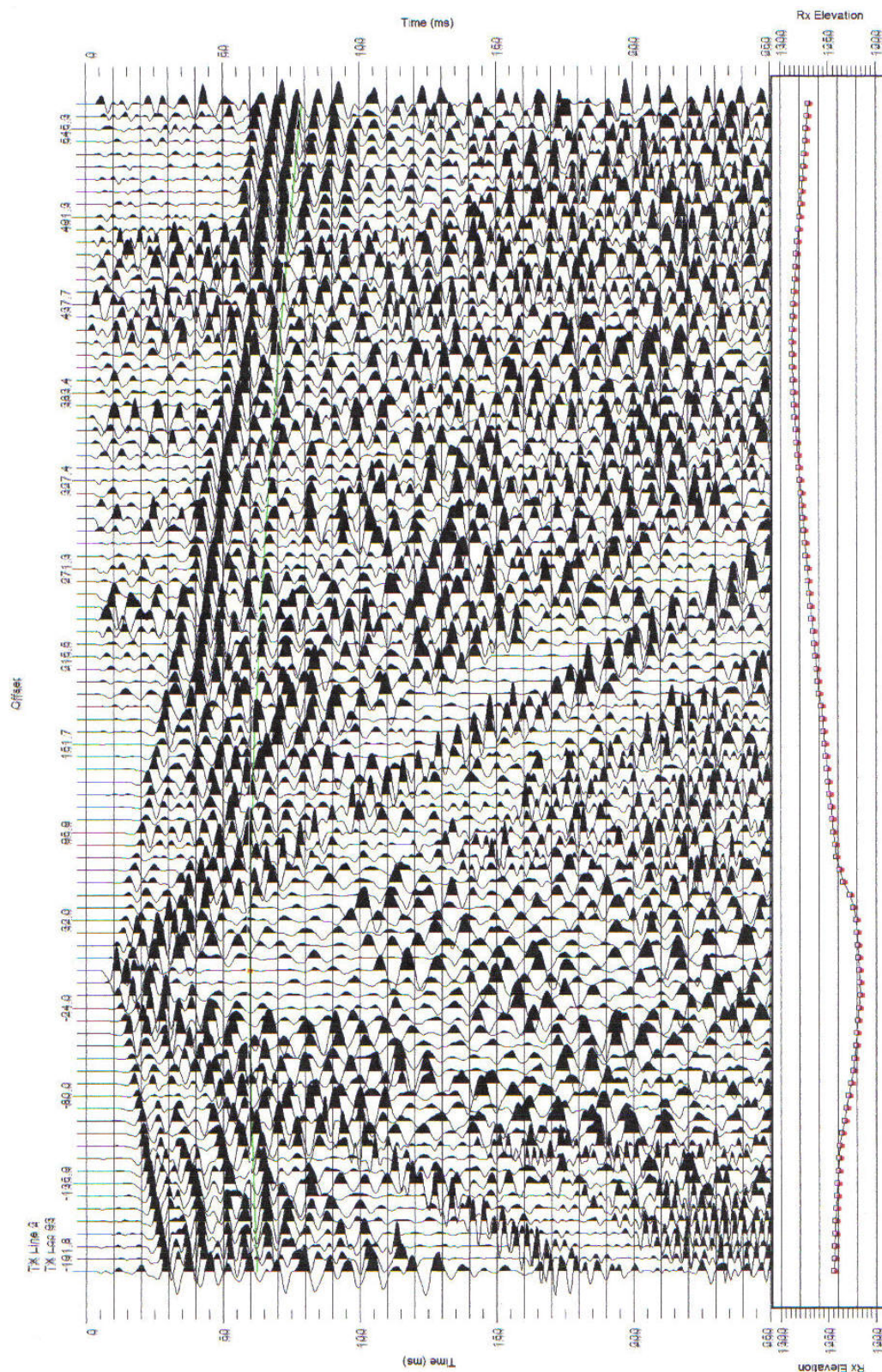


Figure 4. A sample shot gather taken from seismic Lline 1C. Each seismic trace is 8 ft apart.

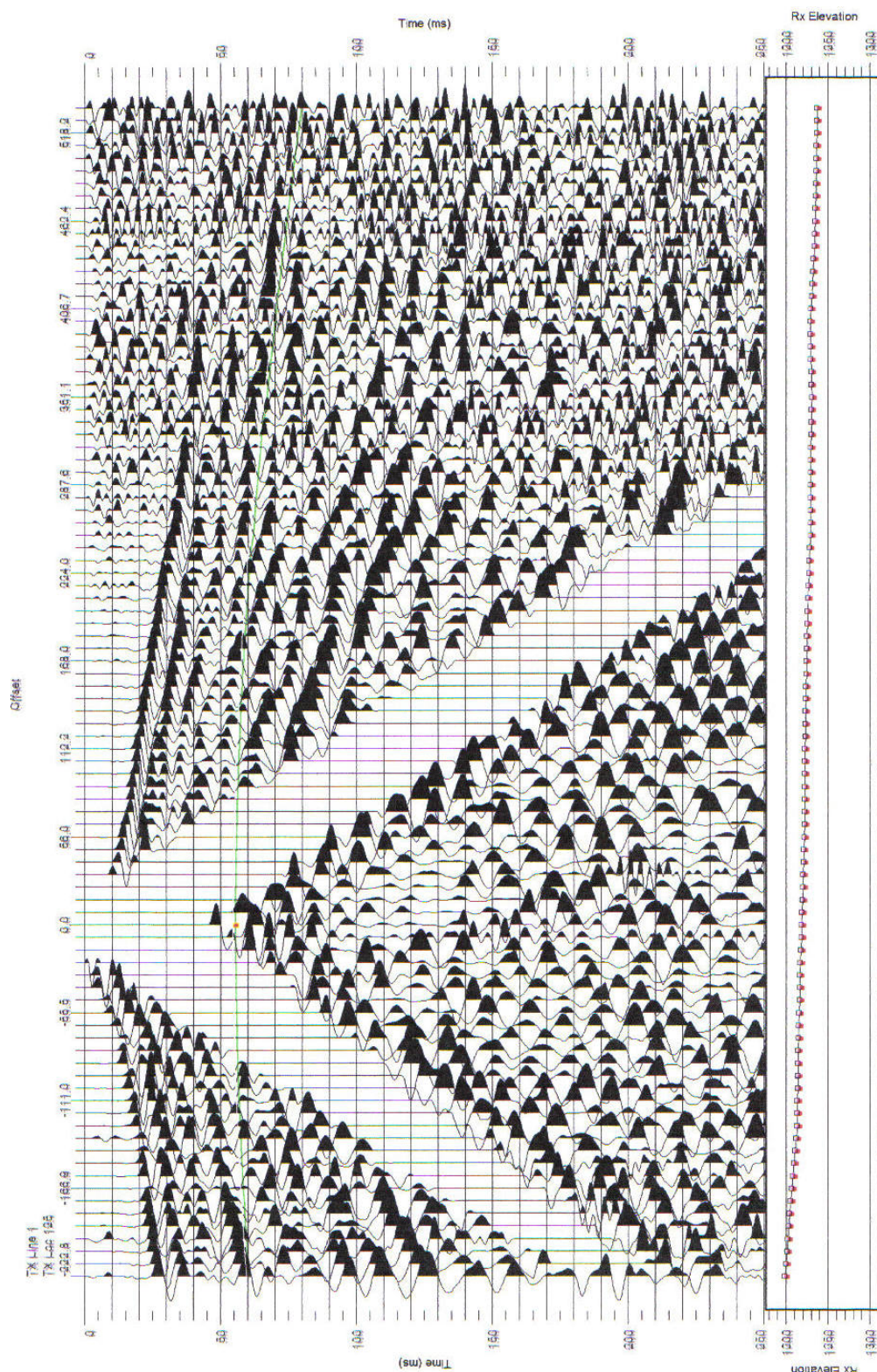


Figure 5. A sample shot gather taken from seismic Line 2B with airwave mute applied. Each seismic trace is 8 ft apart.

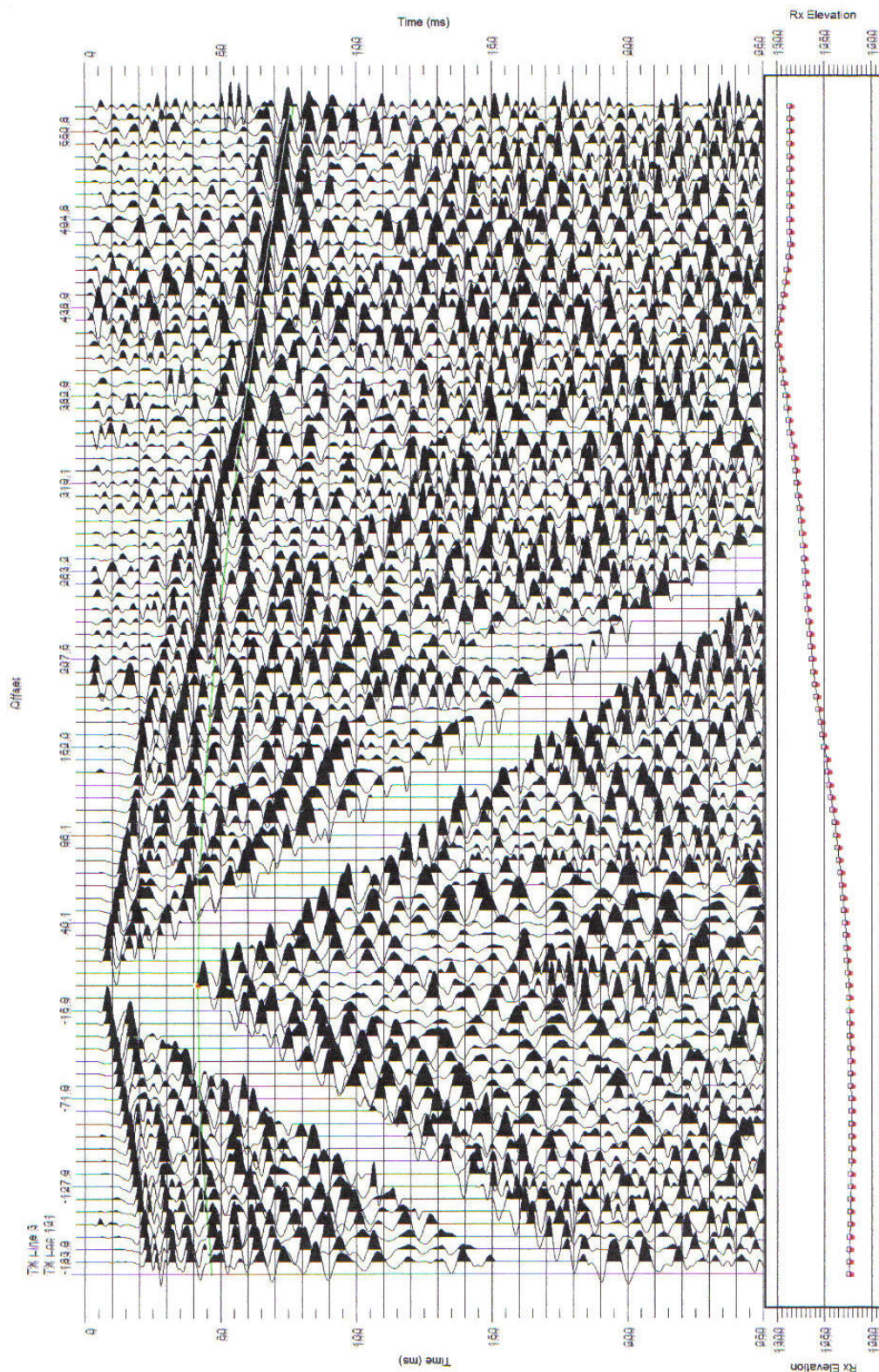


Figure 6. A sample shot gather taken from seismic Line 3A with airwave mute applied. Each seismic trace is 8 ft apart.

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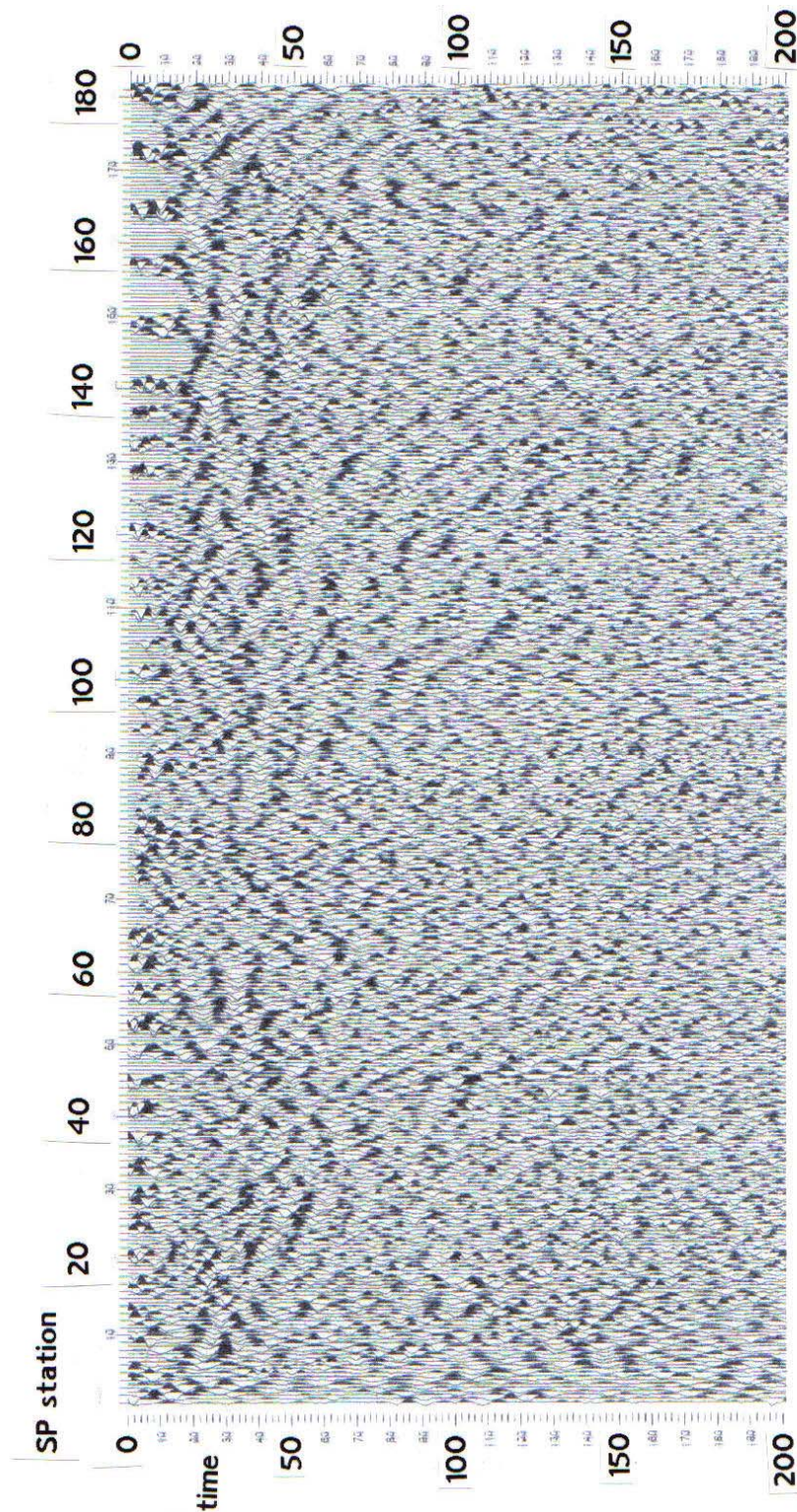


Figure 7. Brute stack section of Line 1C. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

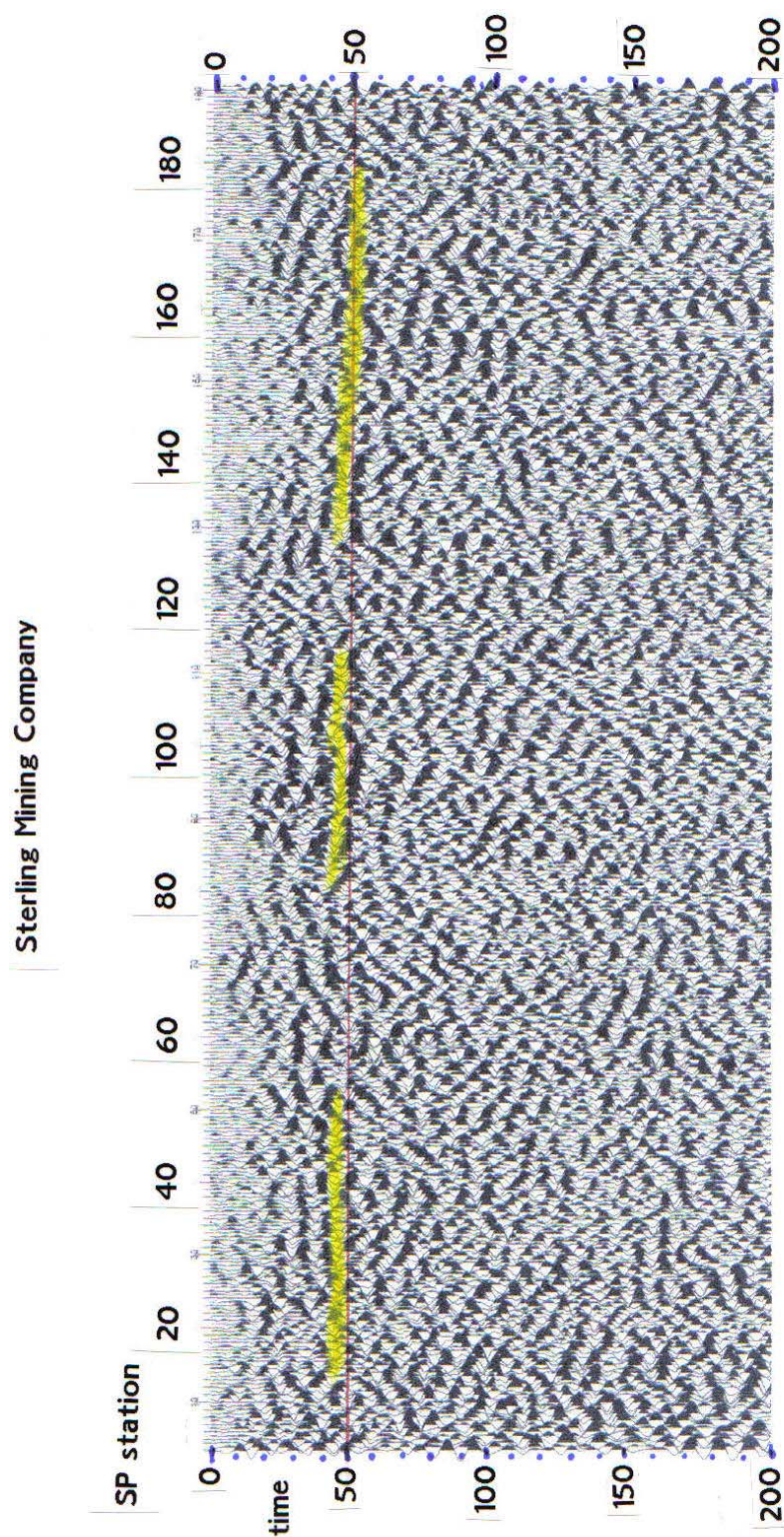


Figure 8. Final stack section of Line 1C. Interpreted coal seam horizon is highlighted in yellow. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

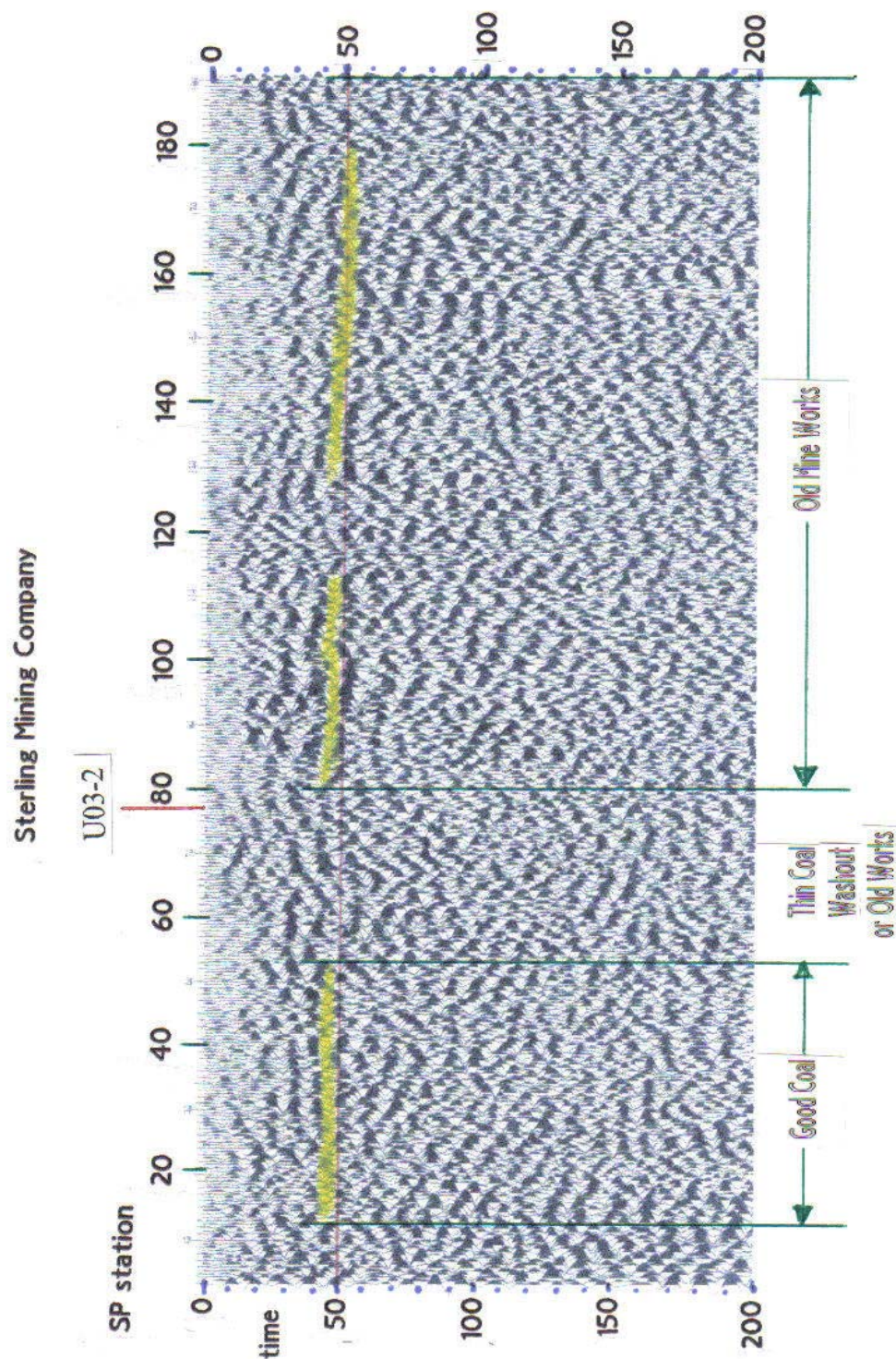


Figure 9. Interpreted seismic section of Line 1C. Borehole U03-2 encountered old mine works and is located near SP-77. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

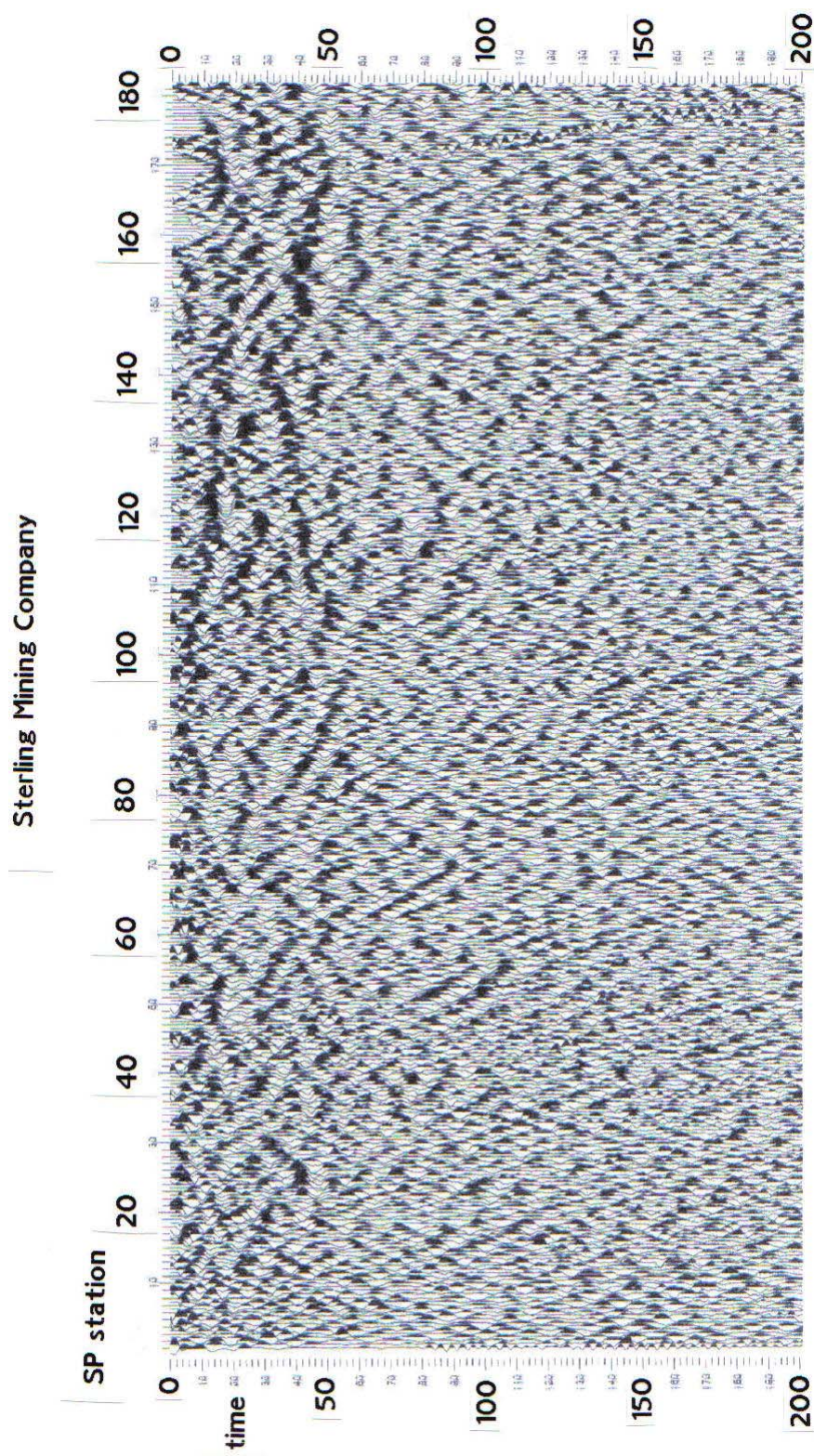


Figure 10. Brute stack section of Line 2B. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

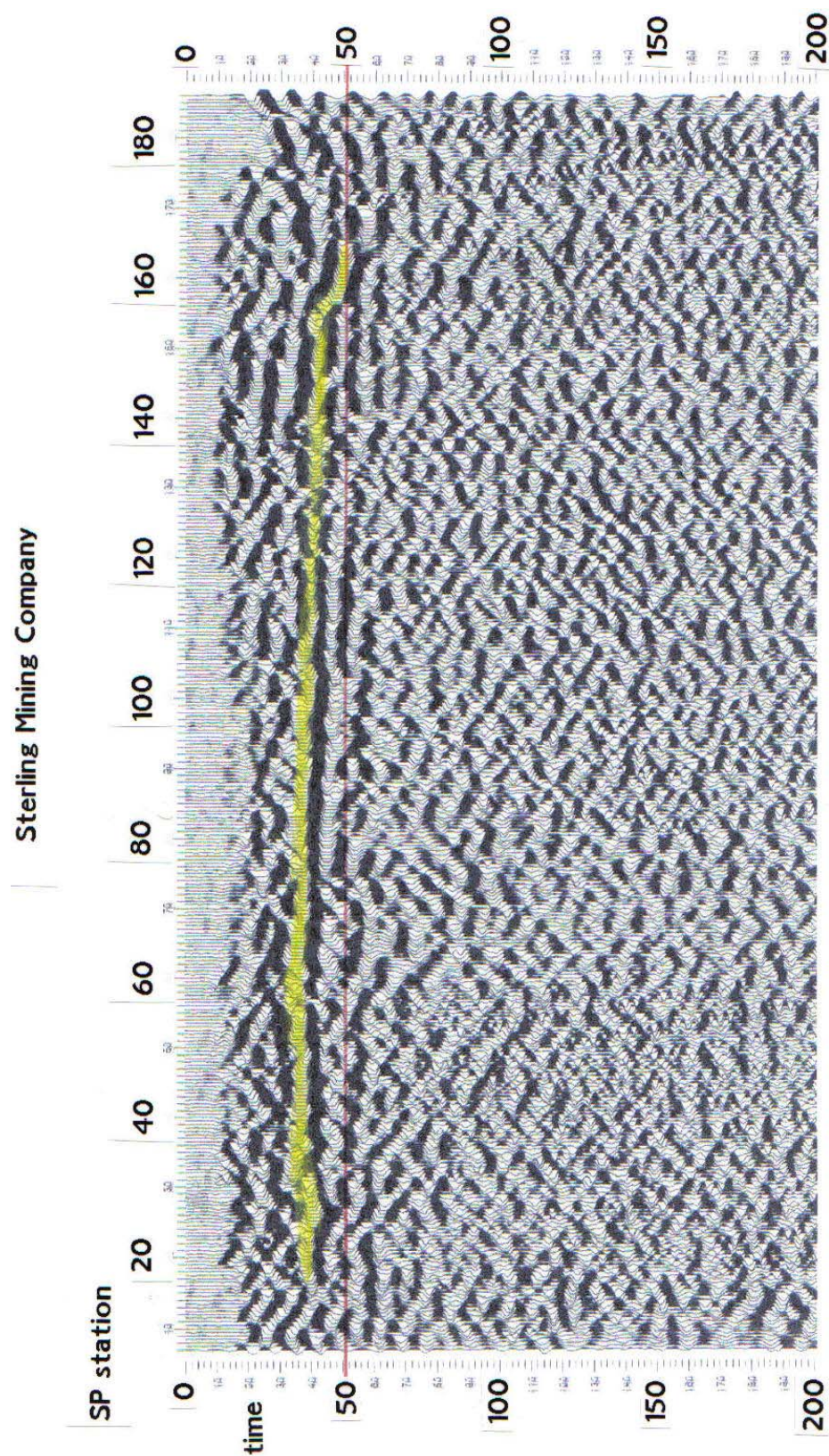


Figure 11. Final stack section of Line 2B. Interpreted coal seam horizon is highlighted in yellow. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

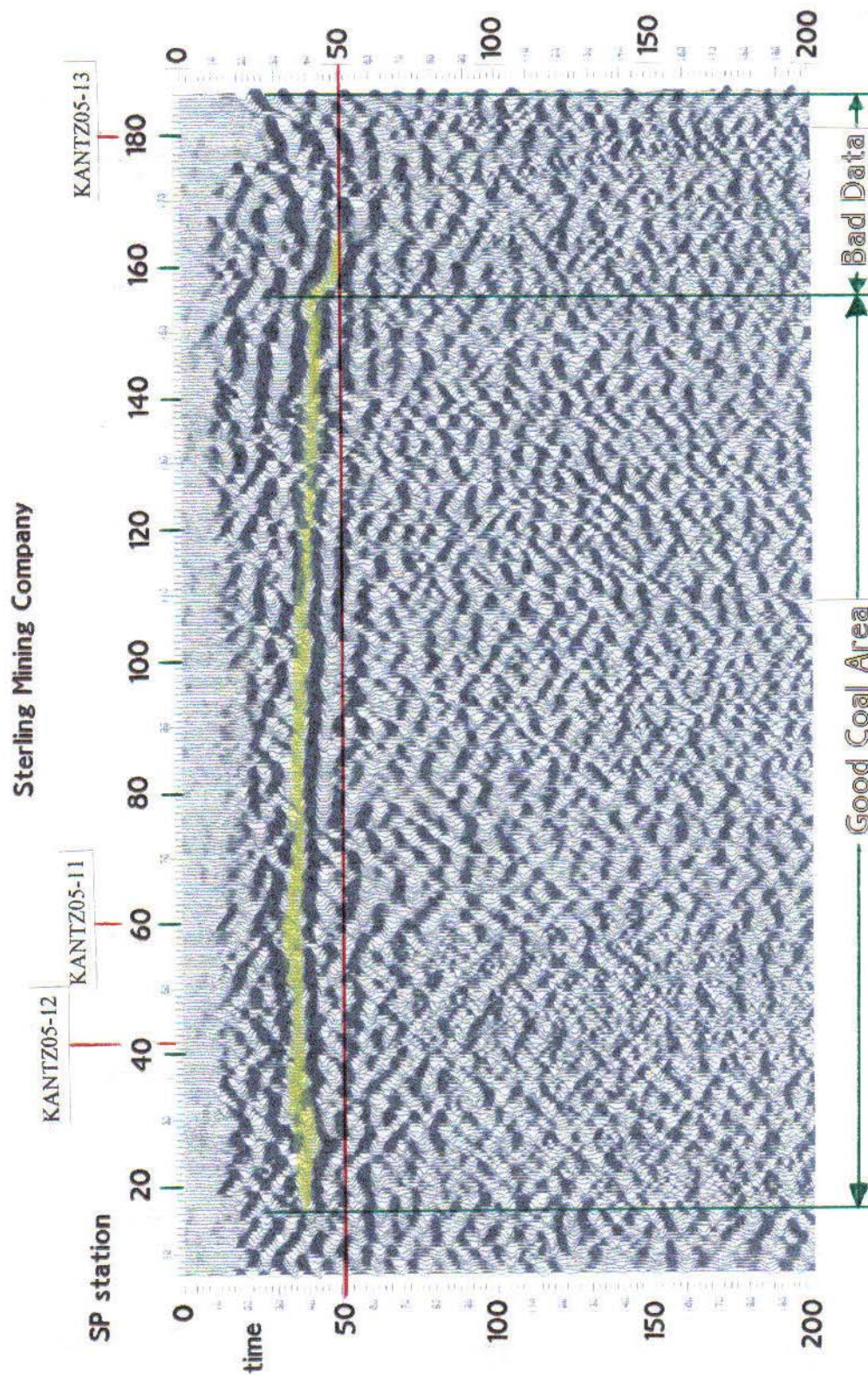


Figure 12. Interpreted seismic section of Line 2B. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

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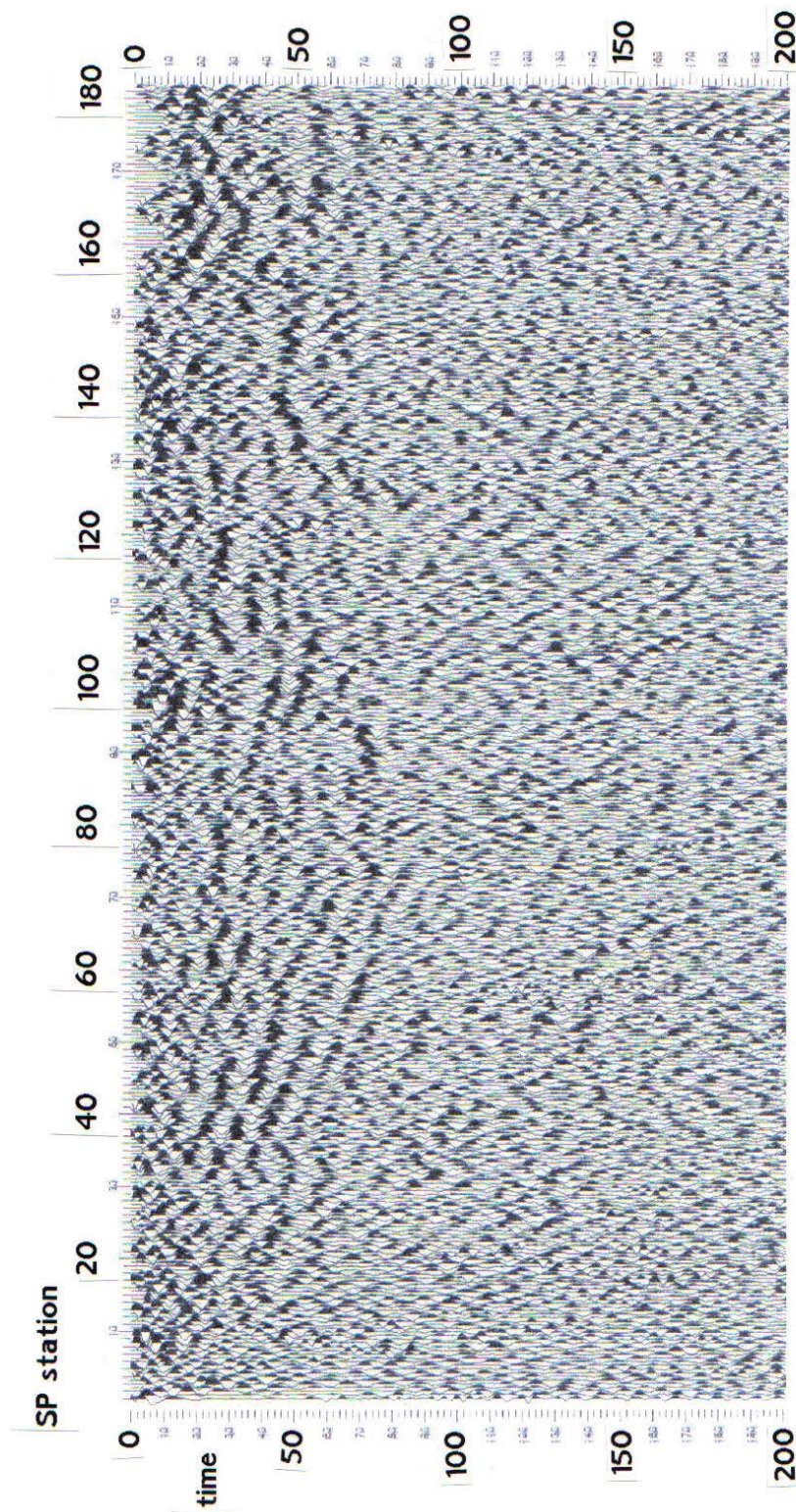


Figure 13. Brute stack section of Line 3A. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

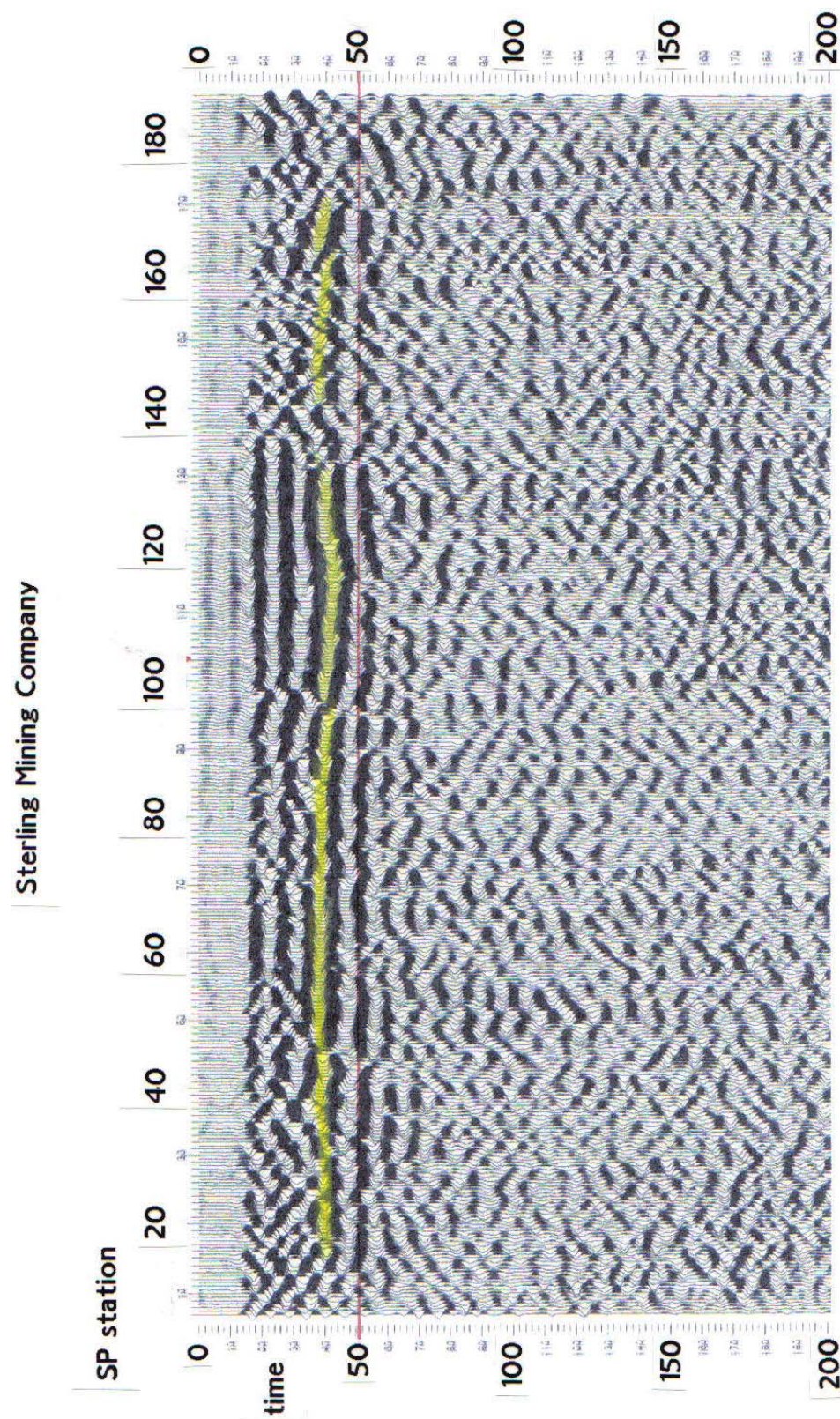


Figure 14. Final stack section of Line 3A. Interpreted coal seam horizon is highlighted in yellow. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**). (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

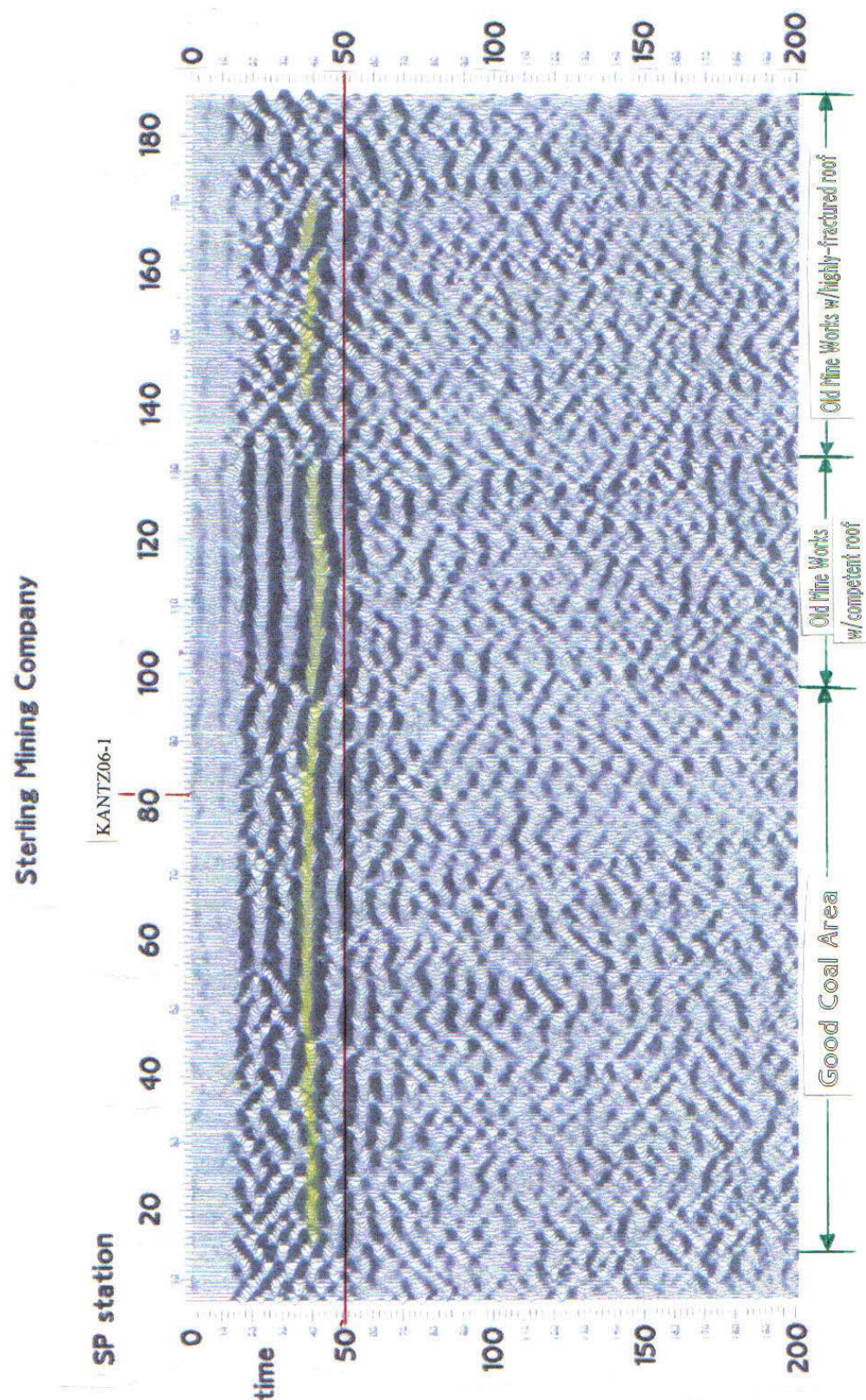


Figure 15. Interpreted seismic section of Line 3A. (Vertical scale in time is **ms** and horizontal scale of SP interval is **8 ft**).

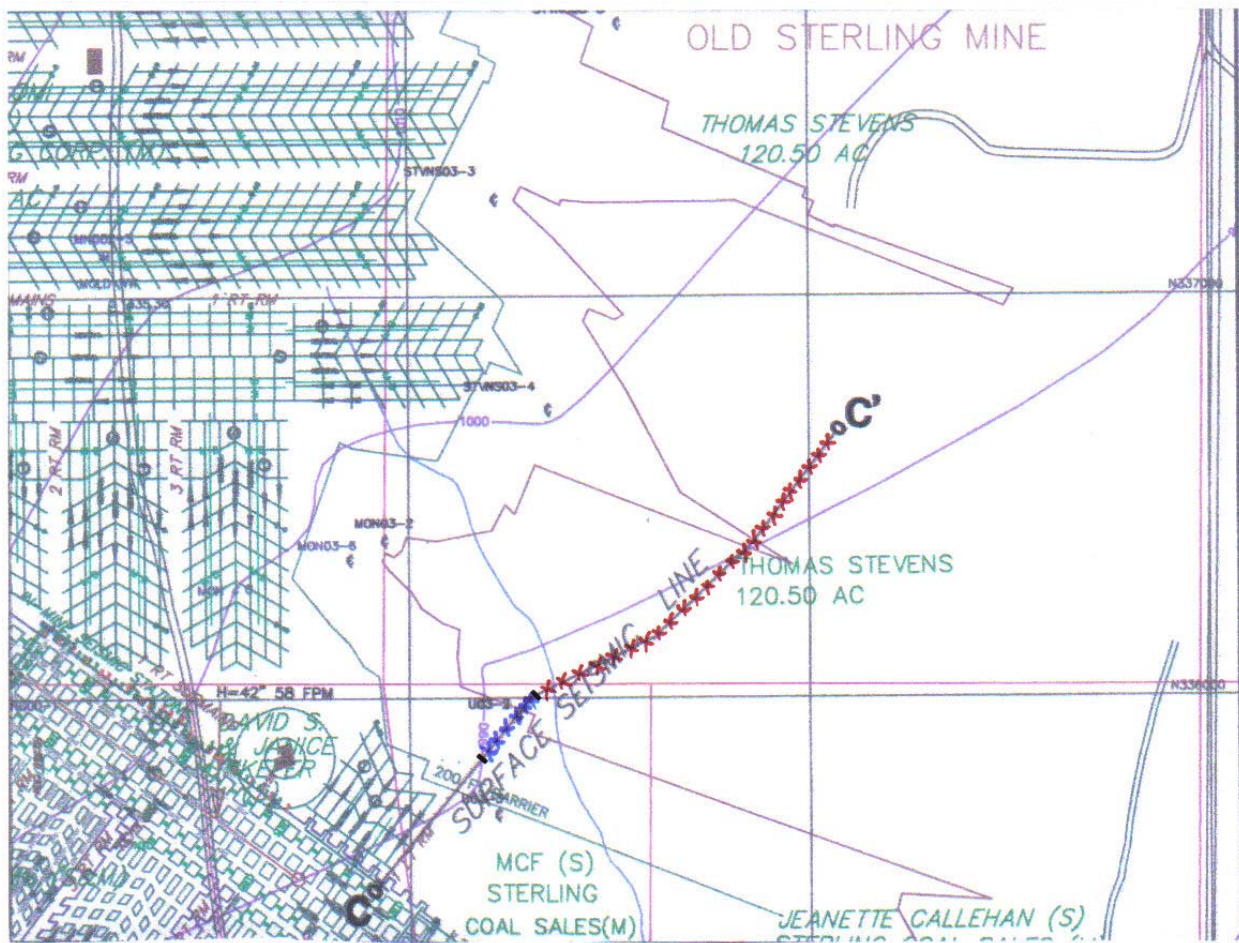
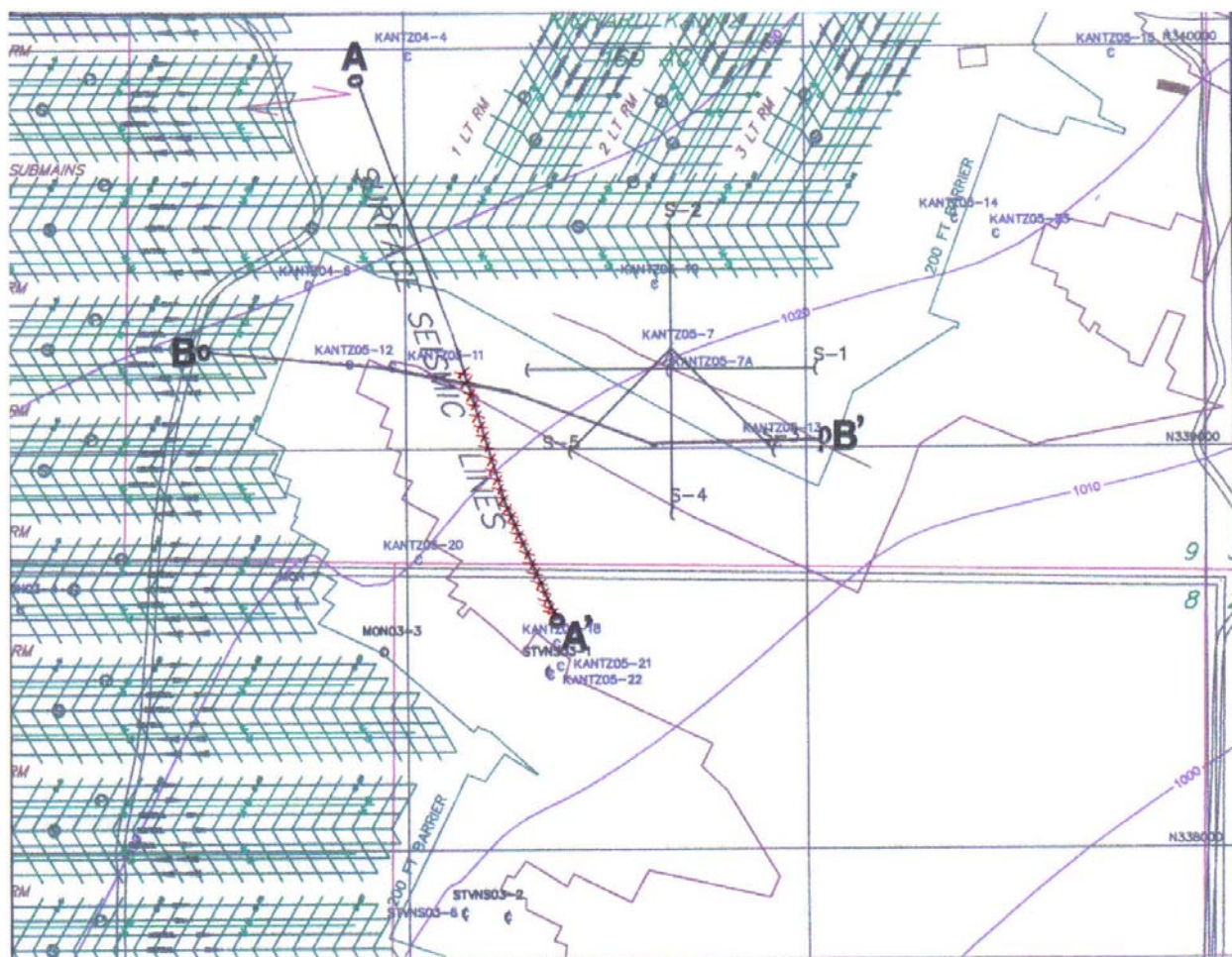


Figure 16. Interpreted seismic data of Line 1C is transposed on the mine map. The latest outline of the old Sterling Mine is shown. The blue cross-hatched segment of the seismic line indicate a potential washout or old mine works. The red cross-hatched segment is associated with the old mine works.



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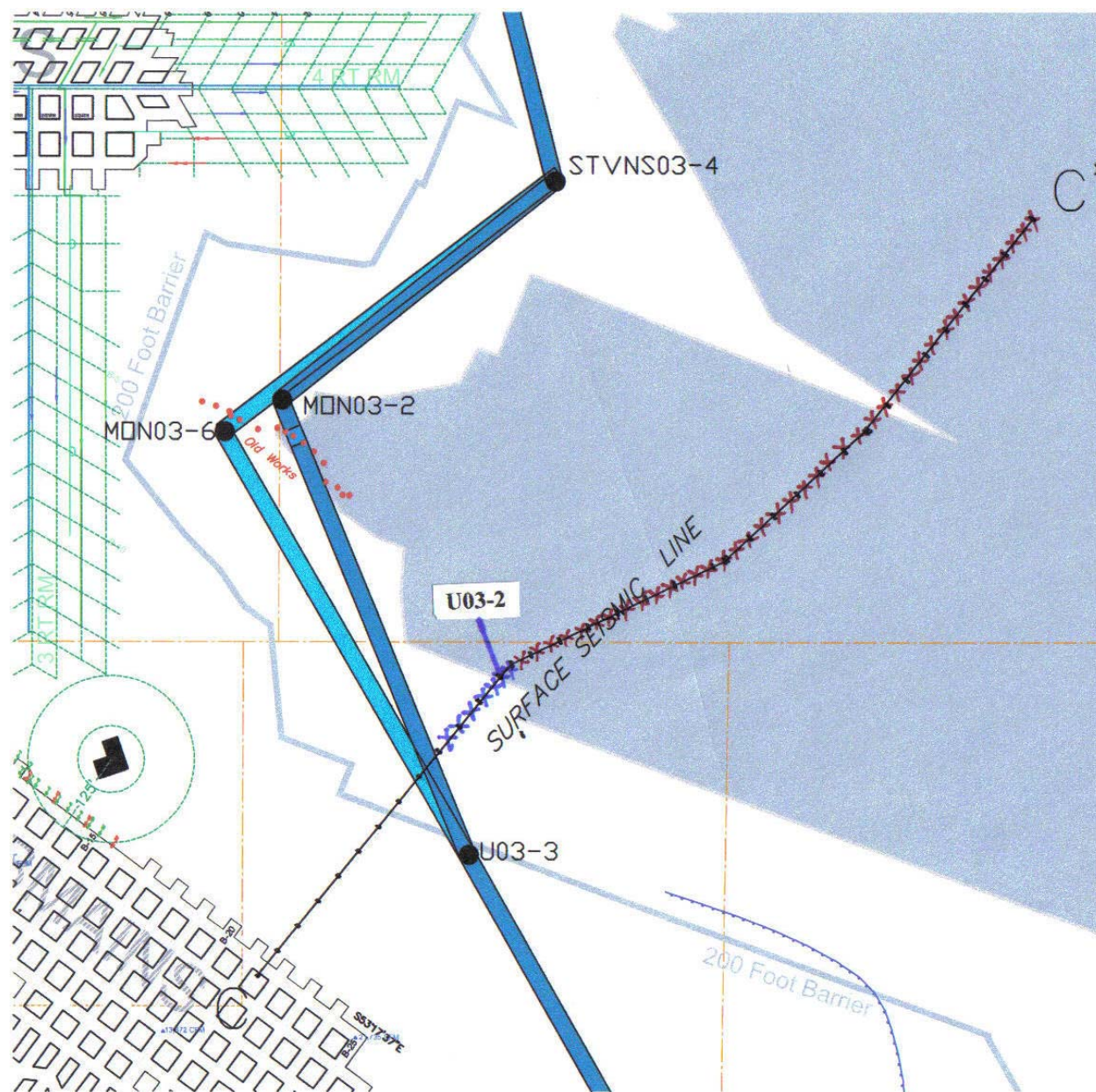


Figure 18. Detected disturbances beneath Line 1C. Blue cross-hatched segment corresponds to interpretation of potential thin coal, washout, or old mine works while the red cross-hatched segment is interpreted to be associated with old mine works.

(Verification – Hole U03-2 drilled near SP-77 and two hole-to-hole tomograms. In this figure, solid blue lines between boreholes correspond to solid coal. A small segment just south of Drillhole MON03-2 detected the tip of the old works.)

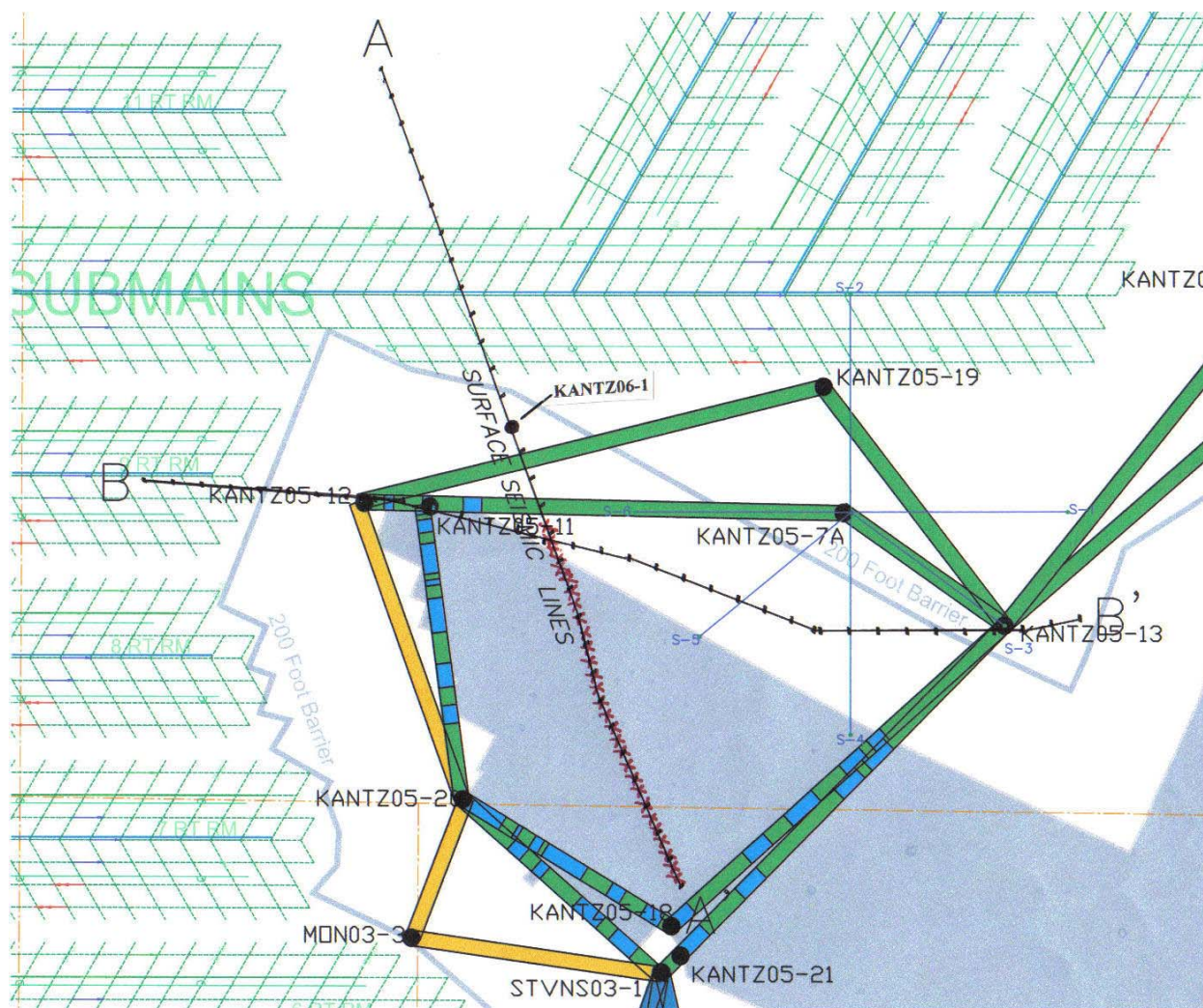


Figure 19. Detected disturbances beneath Lines 2B and 3A were smaller in magnitude than previously thought. A portion of Line 2B straddled the edge of old mine works. The red cross-hatched segment beneath Line 3A is interpreted to be associated with old mine works.

(Verification - As a result of concerns in this section of the reserve, Sterling drilled numerous boreholes around and outside the restricted wooded area to verify the seismic interpretation by conducting hole-to-hole tomography surveys to enhance the geophysical investigation. Solid yellow and green lines indicate solid coal while random blue-green bands were detected old works.)